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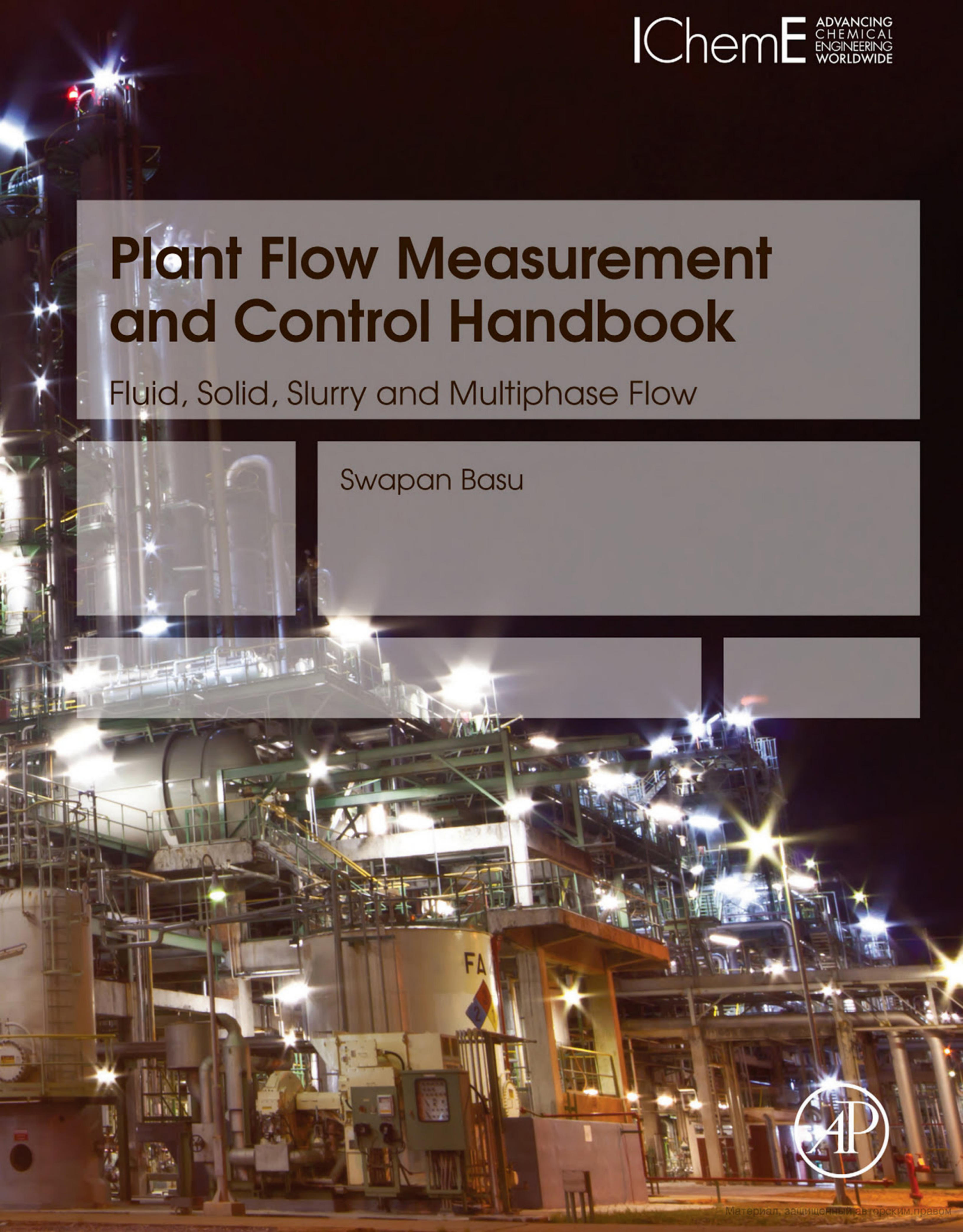
Plant Flow Measurement and Control Handbook

Fluid, Solid, Slurry and Multiphase Flow

Swapan Basu



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Dedicated to Gurudeb, whom I trust
and
to my parents and Kakamoni and
my loving wife and children

Foreword

Flow is a part of life. In our everyday life, it is difficult to imagine a physical system where there is no scope for *flow*. Even the simplest of systems over time require some form of exchange, which can be perceived or represented as flow. Measurement and control of the flow rate of physical materials are extremely important for mass balance and economic reasons and can never be overestimated. Given the wide variations of physical media having a variety of physical and chemical properties, it is natural that there will be a need for dedicated flow meter and/or flow-metering device types to suit specific needs. One of the unique features of this book is that it caters to all types of flow: fluid, solid, slurry, and multiphase; and details treatise on measurement, communication, and controls. The book in each section is dedicated to the description, specification, installation, calibration, and custody transfer (where applicable) of different types of flow meters, flow devices, flow converters, along with fieldbus communication. The inclusion of modern communications systems, applications of these meters in safe as well as hazardous conditions, safety lifecycle and flow meters, as well as flow converter enclosure details have also enriched the book.

Although there are books that have covered these areas separately, there was no single book to cover all these types of flow-metering devices with required details mentioned above in a single volume. Starting with basic flow-measuring principles it covers head type flow meters, open channel flow measurement, PD flow meters, velocity and force type flow metering, mass flow meters, slurry flow measurement, solid flow meters, multiphase flow meters, special flow metering devices (including cryogenic flow measurement), flow conditioning along with the application of different flow meters in different plants over twelve chapters and seven appendices. I felt that the book offers a fine balance between fundamental details, theoretical analysis with required mathematical details and formula, and practical issues related to design, installations, and calibration custody transfer (as applicable). The book offers detailed applications not only to plants of different types and sizes but for flow meters in other applications also.

The author of this monumental work, Mr. Swapan Basu, has a rich industrial experience in instrumentation and control engineering in India and abroad, with myriad process design and commissioning exposures to his credit, and maintains a continuing interest in the latest developments in his field. I truly feel that the book which developed, often drawing from the author's personal industrial experiences, would be extremely helpful to practicing engineers as well as for freshers in the field. This book is extremely helpful for civil, mechanical, and process engineers dealing with flow systems in plants and processes.

I am delighted to know that this book has been selected by **IChemE** in their series of publications.

I wish the author all the success for the book from his efforts.

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Preface

In our daily life we always flow in one form or the other. The most common forms of flow are flow of air and flow of water. It is difficult to imagine a physical process or system without flow.

The physical and chemical properties of physical media have wide variations, giving rise to different kinds and types of flows. Some media may be lighter or some may be heavier, and some may be highly viscous, while some may have high turbulence. In the case of solid flows there will be variations with respect to flowability depending on the bulk density and other properties of solids. Depending on the rheological properties there will be variations in slurry flow measurements. In the case of multiphase flow, depending on the fractions of solids, liquids, and gases, there will be differences in flow measurement principles. While the majority of fluid flows are Newtonian, there will be some flows which are non-Newtonian. In order to cater to all these requirements there will be different kinds of flow meters working on different measuring principles and technologies. This book covers design details, sizing calculations, specification, installation, calibration, and application notes for each of the flow meter types.

In Chapter I, flow measurement principles along with the basic technology behind different kinds and types of flow meters pertinent to fluid, solid, slurry, and special flows, along with multiphase flow meters, have been discussed. While discussing this, a detailed account on the basic theory of measurement with mathematical deductions & equations, and physical and mathematical details on the mechanics of flow metering have been covered. Special emphasis has also been put on the methods of selection of flow meters which can cater to the requirements for various applications. Discussions have been put forward on calibration needs and methods also. Chapter II has been dedicated to head type flow measurement and variable-area flow meters. The discussions include different kinds of primary flow elements, along with detailed discussions on fluid mechanics. The pros and cons of various differential flow elements along with their applications have been covered.

Open channel flow metering, with details of hydraulic design, are used for measurement of large flows of water, such as in rivers/dams. Chapter III, dealing with open-channel flow measurement, discusses in detail various hydraulic structures meant for open-channel flow measurement. Details covered here include sizing and design calculations for these structures with design formula and measuring methods. A number of sensors covering both mechanical as well as electronic types, such as US types, have been included in this chapter. A wide range of PD meters is available for measurements of different fluid types, especially for highly viscous fluids like those found in oil and gas applications. Chapter IV has been dedicated to PD meters to cover almost all types of PD meters available, with their application areas.

Velocity and force are commonly used parameters for fluid flow measurement. Turbine meters, electromagnetic flow meters, ultrasonic flow meters, vortex/swirl metera, and fluidic meters, such as Coanda effect meters, are examples of velocity type flow meters covered in Chapter V, which also includes target flow meters based on the force-measuring principle. Apart from volume measurements of fluids discussed above, mass flow measurement based on Coriolis principles and twin-turbine flow meters have been covered in Chapter VI. This chapter also discusses why and how mass flow measurement is accurate and true flow measurements for fluids.

Rheological properties of fluids actually govern slurry flow. There are different techniques, such as wedge meters, along with special types of conventional meters redeployed for slurry flow measurement. Some fluids, which are non-Newtonian, need special attention. In Chapter VII these have been covered.

Solid flow measurement and their requirements are quite different from those applicable for fluid flow measurement. Chapter VIII has been dedicated to account for the same. Starting from standard weight measurements such as centripetal, impact scale, weigh feeder, and belt weigher, detailed discussions have also been presented on Coriolis type flow measurement, gravity-filling machines, road vehicle weighing, and railway weighing. Also, noncontact type measurements, such as microwave type flow meters and radiometric flow meters have also been described.

Multiphase flow is quite commonly encountered in oil and gas fields, and many other areas demand completely

different kinds of measurement techniques. There is a wide range of technologies involved in the measurement of multiphase flow measurement, these are: gamma ray, PIV, LDA EIT (including virtual measuring systems), tomography types including gamma/X-ray, neutron/positron, optical, ultrasonic electrical impedance with computerized tomography (CT), to name a few. Detailed accounts of these, along with conventional measurement types, and their applications depending on multiphase fluid conditions have been enumerated at length in Chapter IX.

Chapter X is dedicated to various flow sensing types, flow gages, flow switches (for solid flow also) types, along with standard mechanical meters, such as water meters. Detailed discussions have been presented on cryogenic flow measurement and various kinds of flow pickups used in flow meters.

Flow-conditioning devices are basically accessories for flow measurement used for accurate fluid flow measurements. DPTs and MVTs are major devices for flow measurement with head type flow measurement. Various flow-computing devices, controllers, batch controllers, and dispensers are used in flow measurement systems as secondary devices. In Chapter XI, discussions on these, along with energy flow metering and metering pumps have been included to complete the discussions on flow measurement systems.

Detailed discussions on flow measurement problems and plant-specific issues in various power, process, and industrial plants have been discussed in Chapter XII.

Engineering unit conversions, material selections, and mechanical details of flow meters and their accessories are very important for flow meter applications. All these required data and design details have been appended to this book. The importance of safety lifecycle, hazardous applications, and enclosure details for flow measurement cannot be overestimated, so required details have been appended to this book along with discussions on device communications.

An attempt has been made to maintain the delicate balance between theoretical and mathematical details and the author's research work on the subjects through global industrial plant experiences over nearly four decades. The efforts of the author make the book suitable for practicing engineers in industries as well as for budding engineers and advanced students.

Acknowledgments

At the outset the author wishes to put forward his thanks and gratitude to the ***International Electrotechnical Commission (IEC)*** and ***IChemE***.

The author is thankful to IEC for granting permission to use some of their figures from IEC 61508 and 61511 in the book and would like to acknowledge the following:

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The author is extremely thankful to the Institution of Chemical Engineers (***IChemE)*** for selecting the book in their series of publications.

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Last, but not the least, the author would like to thank his children Idai (Raj) and Piku (Deb) for their continuous inspiration and support and he would like to convey special thanks to his wife, Bani Basu, for managing the family with care within limited resources and encouraging the author when writing book. The author feels great pain in the sudden demise of his uncle (the late K.K. Basu), who was responsible for bringing the author to this position, and so the author acknowledges his immense contribution for all his works.

The author sincerely acknowledges the support he has received, without which it would have been impossible to publish the book.

CHAPTER I

FLOW METERING: GENERAL DISCUSSIONS (*AN OVERVIEW*)

Chapter Outline

1.0.0 INTRODUCTION

I still remember the interview day of my first job, I was asked by one of the interviewers, "What are the major parameters measured for boiler monitoring?" As a fresh engineer and without thinking through the question, I immediately replied "steam flow" (probably as it was a boiler, steam came into my mind). One of the interviewers (probably) was surprised! He stared at me and asked "How come you thought of steam flow first?" Then it was my turn to be surprised with the counter-question. I really had no answer! Hopefully I could guess now, after so many years in the process industry, why there was a counter-question. Of the four major parameters, i.e., pressure, temperature, level, and flow, normally measured in all process control instrumentation, flow measurement is the most complex, as there is no direct means to measure it. For flow measurement one has to depend on one or other of the related parameters, which vary with the associated conditions. The historical background of flow measurement has been illustrated in Fig. I/1.0.0-1.

From elementary physics it is known that there are three states of matter. These include the following.

- *Solids:* The molecules of a ***solid*** are usually closer together and the attractive forces between the molecules of a solid are so large that a solid tends to retain its shape.

  Fluids: In the case of fluids, the attractive forces between the molecules are comparatively

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The concept and understanding of "FLOW" comes after the publication of "Hydrodynamica" in 1738 by the Swiss physicist and mathematician Daniel Bernoulli (1700-1782). He actually framed famous fluid equation. However earlier days also people had some concept of flow, Aristotle viewed the motion which involves a medium that rushes in behind a body to prevent a vacuum. Bernoulli introduced the concept of the conservation of energy for fluid flows. So when a restriction is put, there will be increase in fluid velocity hence kinetic energy but there will be loss in static pressure, hence energy.

FIGURE I/1.0.0-1 Historical background of the concept of fluid flow.

much smaller and do not retain their shapes. A fluid may be either a ***gas*** or a ***liquid.***

- *Gas:* The molecules of a gas are much farther apart than those of a liquid and the force of attraction is weak. For this reason a gas is very compressible, meaning that upon removal of all external pressure, it tends to expand indefinitely.
- *Liquid:* A liquid has molecules closer than a gas and the force of attraction is greater than in a gas. A liquid is relatively incompressible—meaning that upon removal of all external pressure except its own vapor pressure, the liquid does not expand indefinitely.

  Vapor: A vapor is a gas whose temperature and pressure are such that it is very near the liquid phase. Thus steam is considered a vapor because its state is normally not far from that of water.

Naturally, flow measurement of each of these phases and mixing of them requires technical approaches which shall be dealt with in detail in this handbook.

Again of the fluid flow measurements, compressible fluid flow measurement is comparatively more complex than for noncompressive fluid/liquid. Similarly, flow measurement of multiphase and slurry is much more complex. According to B.G. Liptak "No industrial measurement is more important than the accurate detection of the flow rates…." Naturally the following question comes to mind "*Why?*" On account of the following reasons, the importance of flow measurement in industrial as well as social applications has grown exponentially:

- accounting purposes and leakage management;
- custody transfer from supplier to consumer (especially in the oil and energy sectors);
- essential in any process and manufacturing plant, including quality management in batch processes, dosing, etc.

As a result, efforts have been made to improve the quality and performance requirements from flow-metering devices demanding higher or better accuracy, linearity (as applicable), and a better turndown ratio. The safety life cycle is now becoming a part of any devices or systems leading to demands for higher stability, reliability, and safety on these flow devices. Also, in order to match with the development of electronics (especially embedded electronics and micro controllers) and communications, additional demands have been placed on flow devices to support software and communication facilities. Various points discussed so far a few examples of generic issues, in specific there could be wide variations in the fluid properties between two measurements (even in the same plant, e.g., air flow, coal flow, steam flow, and feed water flow in power plants) even in the same plant and/or in various industries. The material may be solid, liquid, or gas and single or multiphase. The material may be abrasive, corrosive, explosive/flammable, or toxic, etc. The flow could be in an open channel or in a closed pipe or a duct. There can be large variations in the size (and geometry) of the pipe/duct or channel (e.g., a few mm to a few meters). There can also be wide variations in pressure (from a vacuum to a few hundred kg/cm^2) and temperature (cryogenic to a few hundred degrees Celsius). Some fluids may be conductive (water) and some are very much less conductive (oil). In some cases volumetric flow measurements are acceptable, e.g., in gas fuel stations—a car filling X liters of petrol or in irrigation XXX

cusec of water release. On the other hand, in a few cases it is necessary that flow measurements are in mass, e.g., XXX tons of coal per XXX MWH energy, or XXX tons of gypsum per XXX tons of cement production. From the above discussions it is evident that measuring instruments need to have at least the following qualities [1]:

- high overall accuracy;
- well-understood functionality;
- better design and easy sizing;
- established installation procedure with less dependency on pipe straight run;
- easy operation and maintenance;
- testability even without a test bench;
- self-monitoring and diagnostics;
- suitably developed for safety life cycle;
- communication ability.

In order to cater to these requirements there are quite a good number of technologies that have been developed and are available for flow measurements. Therefore, the task of the designer in selecting a flow meter for a particular service is becoming more and more complex. This is clear from a simple example: Steam flow measurement, with which the discussions started, can be measured by head type flow measurement technique, vortex meter, turbine meter, or Coriolis mass flow meter, to name a few of the seven technologies used for steam flow measurement. The question is which one will be best suited for an application. Even within head type measurement there are choices of flow elements, such orifice plate, flow nozzle, etc. Therefore, it is extremely important to see which is best suited for a particular application as well as being economical. Overview discussions have been put forward in this book to guide proper selection of flow-measuring, computing, and controlling devices. Emphasis has been put to look into the sizing, design calibration, and installation aspects of each type of flow device. Also, short discussions have been put forward to cover commissioning and operation and maintenance (O&M) of these flow devices. Other important issues in connection with flow measurements are various international standards and units and unit conversions. In order to understand the implications of these standards in flow measurements it is essential to have some fundamental knowledge of fluid mechanics and physics. In this book short discussions on these are given.

1.0.1 DISCUSSIONS COVERED IN THIS BOOK

Prior to moving to technical details discussions in this book have been arranged to ensure that the reader is well aware of detailed content of the book.

1. Chapter I: This chapter gives initial discussions to portray an overview of basic material characteristic properties and flow metering technology. The coverage includes relevant parameters in general that affect flow measurement, fluid mechanics, and physics, and flow profile—laminar flow turbulent flow. An overview is provided of various flow-measuring principles, with short discussions on the pros and cons. Types of flow meters and their applications for selection, requirements for good practices of calibration, and installations are the main issues discussed here. The discussions cover both fluid and solid flow measurements and controls including slurry/complex fluid and multiphase flows also. Major terminologies and common issues mostly have been covered in this chapter so as to help to go through subsequent chapters.
2. Chapter II: Head type flow-measuring flow elements covering Bernoulli's theorem and flow calculations. Also covered are specification sheets, sizing, constructional details, straight length requirements, pressure loss, etc. for orifice plates, flow nozzles, Venturi tubes, Dall tubes, Pitot tubes, Annubar, Krell's orifice, V cone and elbow type flow measurement. Wedge flow device although operate in in head type measurement principles yet as it is more connected with slurry flow measurement it is discussed in chapter VII. Although variable area flow metering does not work in head type flow measurement principles yet same has been covered here.
3. Chapter III: Open channel flow measurement: Design and sizing of weirs, Parshall flumes, other open channel flow metering elements and level-sensing instruments. Design drawing

specifications, installation, and calibration of the above devices and elements.

4. Chapter IV: Positive displacement instruments: Working principles, pros and cons, design details, specifications, calibration, installation details, pressure loss, and tips for Operation and maintenance (O&M) for positive displacement (PD) flow meters such as nutating discs, oval gear, rotating pistons, rotating vanes, reciprocating type, helical gear bi/trirotors, etc. to name a few.
5. Chapter V: Force/velocity type measurement: Working principles, pros and cons, design details, specifications, calibration, installation details, and tips for O&M for each of the meters including: turbines, paddle wheels, vortices, electromagnetic, target, Coanda effect and momentum exchange, and ultrasonic (transit time, Doppler). This chapter also accounts for some sensing types. Although not velocity type flow measurement but this chapter includes discussions on Target type flow meter also.
6. Chapter VI: General discussions on volumetric versus mass flow, and density issues. Working principles, pros and cons, design details, specifications, calibration, installation details, pressure loss, and tips for O&M for Coriolis and other mechanical mass flow meters as well as thermal mass flow meters.
7. Chapter VII: This chapter has been dedicated for slurry and complex fluid flow measurements. Rheology Newtonian and non Newtonian fluid types and associated fluid mechanics have also been covered. It covers both various flow meters and their applications in industries as well as various plant applications and use of flow meters there have been covered here.
8. Chapter VIII: Solid flow measurement: General discussions and solid flow-measuring techniques and associated physics. Working principles, pros and cons, design details, specifications, calibration, installation details, and tips for O&M for each of the meters including: Coriolis solid FM, microwave and nucleonic solid flow meters, load cells and speed sensors, impact scale, loss in weight and gravity feed, belt scale/belt weigher, weigh feeder. Discussion on Gain in weight (GIW) and Loss in weight (LIW) have also been covered so as to meet the requirements for various filling and dispensing machines discussed in chapter XI.
9. Chapter IX: Multiphase flow measurement: Multiphase flow-measuring concept, two-phase flow measurement, wet gas flow measurement, miscellaneous flow-measuring techniques, multiphase flow measurement with special reference to oil and gas applications. In each case working principles, pros and cons, design details, specifications, calibration, installation details, and tips for O&M are covered. This chapter covers detailed on various measurement technologies such as various tomography principles to name a few —used in flow measurements of multiphase flow measurements, well testing separators etc.
10. Chapter X: Special flow meters, flow gages, and switches: Working principles, pros and cons, design details, specifications, calibration, installation details, and tips for O&M for Hall effect flow meters, flow meters in cryogenic applications, different metering pumps and special flow instruments.
11. Chapter XI: Flow computation and control: This chapter is dedicated to various flow-computing devices from DPTs to MVTs. This also includes metering pumps, energy calculators, dispensing machines, batch controllers, bottling machines, batch controllers, flow computers (density compensation, flow management computer), flow controllers (alarm, ON, OFF, and PID), signal conditioning unit, PLC/DCS interface, rate flow indicator, as well as totalizer. For each case a detailed description, specifications, design data, electrical connections, and interface are given.
12. Chapter XII: Plant application and problems: This chapter is dedicated to general common problems for various plants and plant-specific issues pertinent to thermal power plants, nuclear power plants, oil and gas industries (offshore/upstream, midstream, and downstream), paper and chemical plants, food and pharmaceutical plants, steel and metallurgical plants, cement plants etc.

13. Appendix I: Unit conversions and flow regimes.
14. Appendix II: Material selection guide.
15. Appendix III: Mechanical and piping data.
16. Appendix IV: Custody transfer.
17. Appendix V: Safety life cycle discussion.
18. Appendix VI: Enclosure electrical protection (class).
19. Appendix VII: Device communication.

1.0.2 INTERNATIONAL STANDARDS AND REGULATIONS

There are a number of international standards followed in flow measurements. A short list of these standards is presented in Table I/1.0.2-1 for the reader to go through as required. During the discussions in this book these will be referred to with the correct standard reference. The reader is advised to refer to the latest revision of the applicable standard.

1.1.0 Flow Measurement Basics

As indicated in Fig. I/1.0.0-1, It was physicist D. Bernoulli who first introduced the concept of conservation of energy in fluid flow. From fundamentals of energy conservation it is known that energy associated with any given amount (mass) of material under given conditions is fixed. Fluid mechanics discussed here is concerned with the transformation of pressure energy into velocity and conversely conversion of velocity back to pressure energy. Here pressure energy means the pressure which is capable of creating both kinetic energy (KE) and potential energy (PE) [2]. When any restriction is put in a closed pipeline the velocity of the flowing liquid increases, because the volume in the upstream side must be equal to the volume at the downstream, otherwise there will be an accumulation or dearth of liquid! However, this is never noticed. On account of restriction, the area decreases, so there must be a

TABLE I/1.0.2-1 Some Relevant International Standard Details*

Standard No.	Application Area
ANSI/ISA 84.00.01	See IEC 61511 (modified)
ANSI/ISA 88	Batch control
ASME 19.5	Flow measurement—performance test code
ASME PTC6	Flow nozzle
DIN 19559	Measurement of flow of wastewater in open channels and gravity conduits
EN 29104	Methods of evaluating the performance of electromagnetic flow meters for liquids
EN 60529	Specification for degrees of protection provided by enclosures (IP code)
EN/IEC60529	Specification for degrees of protection provided by enclosures (IP code)
EN/IEC 60079	Explosive atmosphere
IEC 61158	International communication network
IEC 61508	Functional safety of electrical/electronic/programmable electronic safety-related systems—supplier community
IEC 61511	Functional safety of electrical/electronic/programmable electronic safety-related systems—process plant end user
ISA RP 31.1	Turbine flow meter
ISO 10790	Measurement of fluid flow in closed conduits… Coriolis flow meter
ISO 11605	Calibration of variable-area flow meters
ISO 14511	Measurement of fluid flow in closed conduits… Thermal mass flow meter
ISO 15769	Hydrometry—acoustic velocity meters using the Doppler and echo correlation

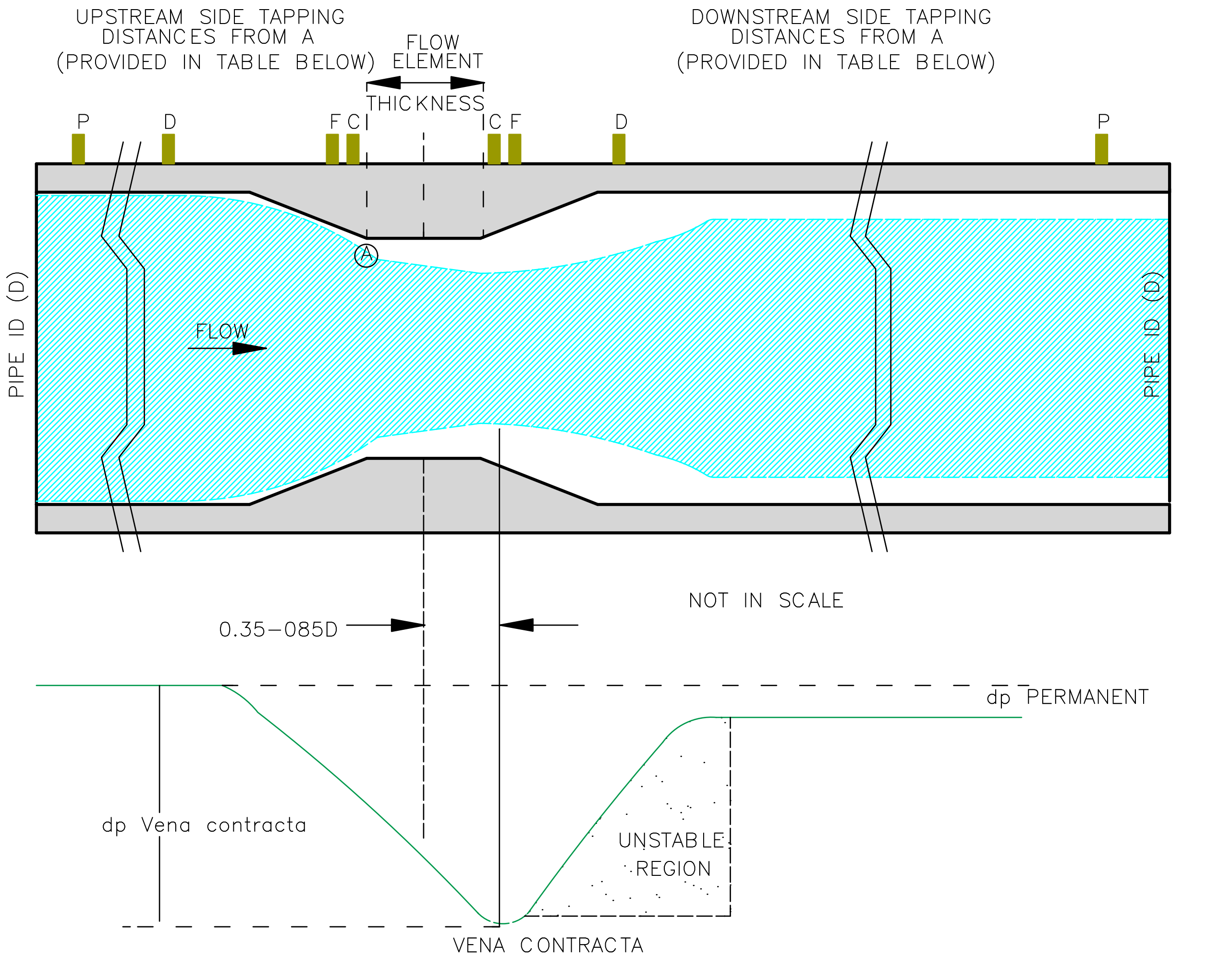
Continued

TABLE I/1.0.2-1 Some Relevant International Standard Details*—cont'd

Standard No.	Application Area
ISO 2714	Liquid hydrocarbons—Volumetric measurement by displacement meter…
ISO 2715	Liquid hydrocarbons—Volumetric measurement by turbine meter systems
ISO 31000	Risk management principles and guidelines
ISO 31010	Risk management—Risk assessment techniques
ISO 4359	Flow measurement structure—Flumes
ISO 4360	Hydrometry open-channel flow measurement using triangular weir
ISO 5167 1	Measurement of fluid flow by means of pressure differential devices… General principles and requirements
ISO 5167 2	Measurement of fluid flow by means of pressure differential devices… Orifice plate
ISO 5167 3	Measurement of fluid flow by means of pressure differential devices… Nozzle and venture nozzle
ISO 5167 4	Measurement of fluid flow by means of pressure differential devices… Venturi tube
ISO 6416	Ultrasonic flow measurement
ISO 6817	Measurement of conductive liquid flow in closed conduits
ISO 6817	Measurement of fluid flow in closed conduits… method using electromagnetic flow meter
ISO 9104	Measurement of fluid flow in closed conduits
ISO 9300	Measurement of gas flow by means of critical flow Venturi nozzles
ISO/TR 12764	Measurement of fluid flow in closed conduits… vortex shedding flow meter inserted circular cross-section conduit running full
ISO1100 1	Liquid flow in open channel
NEMA	For enclosure class
NORSOK I105	Fiscal measurement systems for hydrocarbon liquid

Before moving to technical discussions it is advisable that for any doubt on unit conversions standard books on units and measurements in any standard physics book (graduation level) may be consulted to avoid any confusion.
**Not exact title mentioned here.*

corresponding increase in velocity, so that the volume flow rate matches. Again an increase in downstream velocity means there will be some acceleration. From Newton's second law it is known that for any acceleration there must be some impressed force which, in this case, comes from higher pressure at the upstream. An increase in velocity downstream means that downstream fluid will have higher kinetic energy. From a conservation of energy point of view, there must be a corresponding reduction in energy in another form, which has been transformed into kinetic energy. This transformation comes from pressure energy. Therefore, downstream there is increased velocity of liquid, i.e., higher kinetic energy at the cost of a decrease in pressure, i.e., pressure energy. From the discussions, it is clear that a flow restriction causes an increase in the flowing velocity at the cost of pressure of the flowing fluid as shown in Fig I/1.1.0-1.



NOTE: IN THE TABLE BELOW ALL DISTANCES ARE MEASURED FROM UPSTREAM FACE OF FLOW ELEMENT (A).

TAPPING SYMBOL	TAPPING STYLE	UPSTREAM DISTANCE	DOWNSTREM DISTANCE	REMARKS
C	CORNER TAP			APPLICABLE FOR D < 50mm
F	FLANGE TAP			APPLICABLE FOR D > 50mm
D	D D/2 TAP	D	D/2	APPLICABLE FOR D > 150mm
P	PIPE TAP	2.5D	8	

FIGURE I/1.1.0-1 Concept of fluid flow measurement.

As shown in this figure the highest pressure drop will be slightly away in the downstream side. This point where the pressure drop is the maximum is referred to as the vena contracta. Pressure at the vena contracta is P_{vc}. In head type flow measurements the differential pressure between upstream and downstream of the restriction is measured to compute flow (discussed at length in subsequent chapters). A few typical tapping styles have been depicted in Fig. I/1.1.0-1. When downstream tapping is placed at the vena contracta it is known as vena contracta tapping. Coming back to the main issue, from Fig. I/1.1.0-1 it can be seen that after having the highest pressure at the vena contracta, there will be pressure recovery. However, it never reaches the original upstream pressure. This means that there will be some **permanent pressure loss (PPL)**. This permanent pressure loss through various flow elements can be expressed as a percentage of the total pressure drop. Prior to proceeding further preliminaries of typical characteristics expected of flow meters and the basics of a few other details normally encountered in flow measurements are discussed. This will help to grasp the details in subsequent chapters for flow measurements.

1.1.1 BASIC CHARACTERISTICS AND ASSOCIATED TERMS FOR FLOW METERS

There are a few basic desirable characteristics of flow metering devices. However, this does not mean that all these characteristics need to be present in all flow metering devices. Some of the most important characteristics are listed below.

1. Wide operating flow range, temperature, and viscosity;
2. Less sensitivity toward flow profile and related properties;
3. Smaller permanent pressure loss;
4. Suitability for a wide range of media (material, fluid);
5. Suitable construction material to withstand corrosive and abrasive damage;
6. Simpler calibration;
7. Easy installation;
8. Less maintenance;
9. Immunity to vibration and other mechanical disturbances;
10. Higher sensitivity, reliability, and overall accuracy;
11. Suitable safety life cycle study;
12. Safety issues and safety integrity level (SIL) as required;
13. Suitable output and device communication capability;
14. Suitable output signal for easy integration.

In view of the above it is clear that there need to be judicious applications borne in mind while selecting a flow meter for a particular application. These will be discussed at length in Section 6.0.0 of this chapter. A brief idea of the measurement accuracy (see Subsection 1.1.2.1) of a few flow meter types is illustrated in Table I/1.1.1-1 [3,4].

TABLE I/1.1.1-1 Flow Measurement/Meters (Typical for Idea Only)

Meter Name	Accuracy % FSD	Meter Name	Accuracy % FSD
Orifice plate	2	Flow nozzle	1.5
Venturi	1	Pitot tube	0.5
Ultrasonic flow meter	1	Electromagnetic	0.5
Vortex	1	Cross-correlation	1
Rotameter	1 (of reading)	Hot wire	2
Positive displacement	0.1 (TD 70:1)	Turbine	0.1 (for TD100:1)
Mass flow	0.1 (TD 100:1)	Open channel	2%

FSD, full span division; *TD*, turndown (ratio); highest possible accuracy.

1.1.2 PHYSICS ON FLUID PROPERTIES

Fluid properties shall be discussed here. For basics & explanation standard book on thermodynamics should be referenced. Density and viscosity are two fluid properties which directly influence fluid flow. Density is more important when mass flow computation is desired. Also, both density and viscosity influence Reynolds number (discussed later) which determines flow types, e.g., laminar/turbulent flow. While on the subject, it is better first to define *what density is.* The ***density*** ρ of a fluid is its *mass* per unit volume, i.e., $m/V = \rho$. There is another important term here, specific weight, which is defined below.

Specific weight Υ of a fluid is the weight per unit volume, i.e., specific weight g represents the force exerted by gravity on a unit volume. So, density and specific weight are related by $\Upsilon = 1 \cdot \rho \cdot g$ or $\boldsymbol{\Upsilon = \rho g}$, where g is acceleration due to gravity. The most important fluid property is viscosity.

1. **Physical significance of viscosity and velocity profile:** The viscosity of a fluid puts resistance to the flow, or resistance to any object passing through the fluid. It can be conceived of as the thickness of the fluid. Certain fluids, like water and gasoline, flow rapidly when compared with the flow of honey or motor oil. Since honey or motor oil are thicker, they do not flow rapidly. One must remember that this is not due to density as oils a lower dense than water but flows slowly. This is due to viscosity. This means that thicker fluids like honey/motor oil have more viscosity. Fluid flow may be considered as a *collection* of moving plates, one on top of the other, when a force is applied to the fluid, *shearing* occurs and the viscosity is a *measure of the resistance* offered by a layer between adjacent plates [5].

   This is like sliding these moving plates relative to one another, with the center plate moving fastest and the outermost one at rest. The viscous force between the two plates opposes sliding. This is the reason that it is also referred to as internal friction. The layer of fluid near the surface is nearly at rest with respect to the surface, whereas the speed of the fluid layer at the center will be the highest, as shown in Fig. I/1.1.2-1. *Also, there is no slipping at the center.* Such slips occur due to viscosity. Thus it is seen that viscosity has an impact on the velocity profile and hence flow measurement.

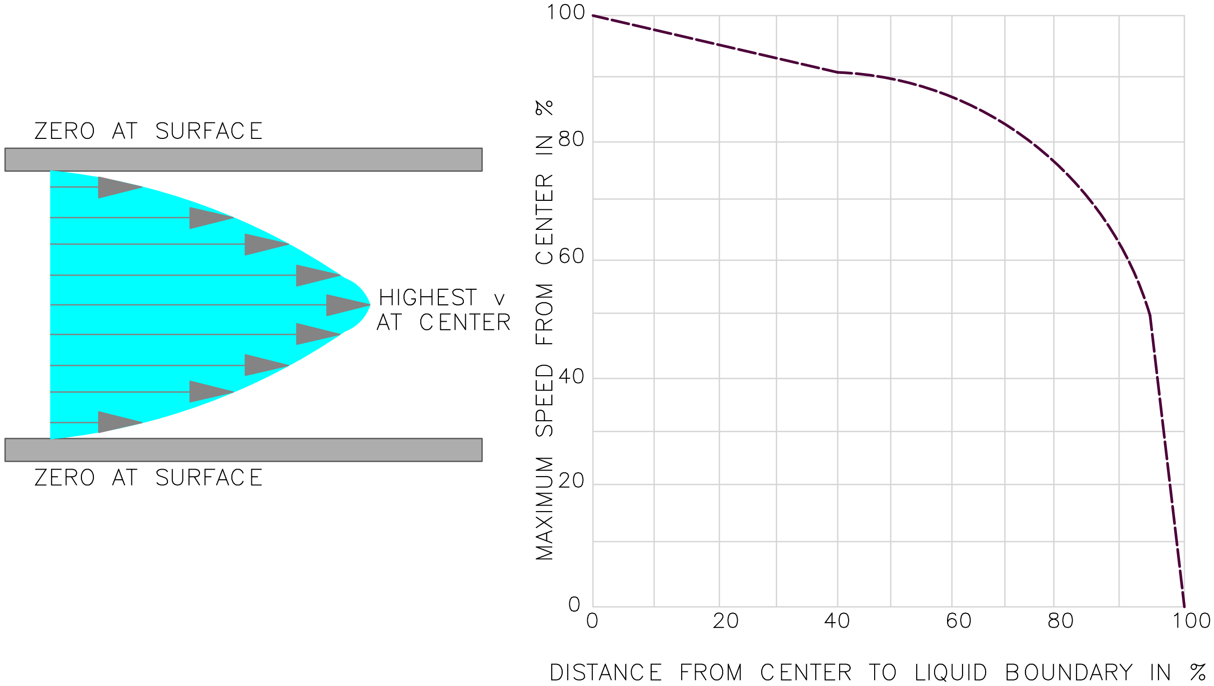


FIGURE I/1.1.2-1 Velocity profile of viscous fluid inside a pipe.

Another important issue obviously comes into mind that if the velocity varies from the wall to the center, which velocity should be considered for flow calculation. *It is normally the average velocity that is taken for flow calculations.*

Therefore, in order to keep the flows going one needs to apply greater pressure at the back of the flow than at the front of the flow, e.g., as when squeezing toothpaste or a ketchup sachet [2]. In a liquid, the cohesive forces between the molecules give rise to viscous force. In the case of compressive fluids, e.g., gas, it comes from collisions between the molecules.

From the above discussions it follows that layers move relative to each other. The velocity at which the layers move relative to each other is therefore the shear rate. Shear rate is proportional to shear stress:

$$\text{Shear rate} \propto \text{Shear stress or Shear stress} = \mu \cdot \text{Shear rate.}$$

This proportionality constant is referred to as ***absolute or dynamic viscosity***. It is important to note that the discussion in the case of Newtonian fluid (refer to Subsection 1.1.2.5 in this chapter) viscosity is independent of shear rate. *Here discussions are presented only on Newtonian fluids. Further generalized details on viscosity are presented in Section 1.1.0 of Chapter VII.* Viscosity is highly dependent on temperature. In the case of liquids, with temperature the cohesive force reduces, and so viscosity falls. In contrast, with an increase in temperature the collision increases in compressible fluid so viscosity increases, as shown in Fig. I/1.1.2-2.

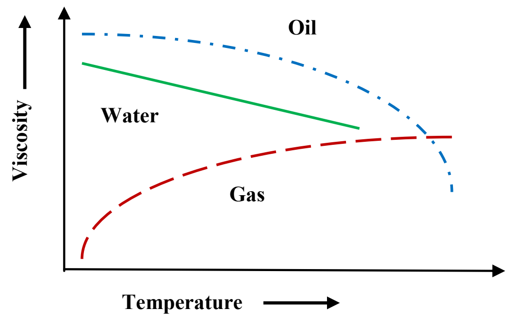


FIGURE I/1.1.2-2 Variation of viscosity with temperature.

There is another way to express viscosity. ***Kinetic viscosity*** is the *ratio* of *absolute* (or dynamic) *viscosity* to *density*, a quantity without involving any force. Kinematic viscosity can be expressed as:

$$\nu = \mu/\rho \qquad \text{(I/1.1.2.1-1)}$$

where ν = kinematic viscosity (m^2/s), μ = absolute or dynamic viscosity ($N\ s/m^2$), and ρ = density (kg/m^3).

2. **Viscosity and Reynolds number:** Related to viscosity there is another important factor—Reynolds' number. Even at constant flow, if the Reynolds number changes, the meter reading will also change. Therefore, it is necessary to calculate the Reynolds numbers at flow extremes (maximum and minimum) to ensure that the corresponding change in flow coefficients is within the acceptable error limits. Now the question is *how the Reynolds number is related to viscosity.* The Reynolds number is a ratio of inertia force and internal friction or viscous force. It is often expressed as:

$$Re = \rho v d_h/\mu = v d_h/\nu(\text{nu}) \qquad \text{(I/1.1.2.2-1)}$$

$$Re = \rho v d/\mu = v \cdot d/\nu(\text{nu}) \qquad \text{(I/1.1.2.2-2)}$$

where *kinematic viscosity* $\nu(\text{nu}) = \mu/\rho$; ρ = density, d_h = hydraulic diameter (discussed later), and v = velocity based on the actual cross-section of the duct/pipe (rather than average velocity). For full pipe hydraulic diameter is equal to full diameter hence both equations equate. These terms are discussed in the next main section. Eq. (I/1.1.2.2-2) is a generalized equation, e.g., *circular pipe* flow.

3. **Measuring variables:** Flow rate measurement is the measurement of ***amount*** passed per unit time— and this could be in the volume flow rate or mass flow rate. From basic physics it is known as an intrinsic property, so, mass flow rate is the ideal measurement value as it

Definitions of <u>NTP</u> and <u>STP</u>:

<u>NTP:</u> Normal Temperature pressure is defined as air at 20°C (293.15K) and one atm (101.325 kN/m^2, 101.325 kPa) Density 1.204 k/m^3. **In FPS it is T: 68°F & P:** ***14.7*****psia**

<u>STP:</u> Standard Temperature and pressure is defined by IUPAC as air at 0°C (273.15K) and 10^5 Pascals. Earlier definition of STP to 273.15K and 1atm (101.325 kPa) has been discontinued. **In FPS it is T: 60°F & P: 14.696 psia**

FIGURE I/1.1.2-3 Definitions of NTP and STP.

is independent of pressure and temperature. However, at times, the volume flow rate is more convenient to measure. The flow rate for coal is normally expressed in tons per hour, whereas air flow rate is expressed in Nm^3/h. Mass flow rate q_m is expressed in Mass/time in kg/s, T/h, etc. and volume flow rate q_v (or only q) is expressed in volume/time in L/s, m^3/s, m^3/h, and Nm^3/h. In cases of volume flow one needs to mention the same at a specified temperature, because the density of materials varies with temperature. For this reason even for noncompressible fluid temperature compensation is often called for (when there are wide variations in temperature, e.g., temperature compensation for feed water flow measurements). In the case of a compressible fluid the situation is totally different. From the ideal gas law it is known that

$$PV = nRT \quad \text{(I/1.1.2-1)}$$

where R is the universal gas constant, and may be 0.08206 (L·atm)/mol·K, when pressure is expressed in atmospheres, volume in liters, and temperature in degrees Kelvin. Here P stands for pressure, T stands for temperature, n stands for mole, and V stands for volume.

From Eq. I/1.1.2-1 it can be seen that volume is dependent both on operating pressure and temperature. Therefore, for compressive fluid flow measurement both temperature and pressure compensation are necessary to take care of density variations. Also, for expressing the volume flow of a compressive fluid, the corresponding operating pressure and temperature need to be known. In order to circumvent such problems usually such volume flow is mentioned at a standardized pressure and temperature. There are two such standard pressure/temperature conditions. These are normal temperature pressure (NTP) and standard temperature pressure (STP) as detailed in Fig. I/1.1.2-3. Therefore, compressible fluid flow is expressed as, e.g., 90 Nm^3/h.

As indicated in the above section, density (ρ) is expressed as mass/volume in kg/m^3, g/cm^3, etc. The discussion presented above is for instantaneous flow rate but not on the total quantity delivered. Therefore, to get total flow one needs to compute the following equation normally done in a totalizer.

$$Q_v = \int_{t1}^{t2} x\,dt \quad \text{where } x = q_v \quad \text{(I/1.1.2-2)}$$

for totalized volume

$$Q_M = \int_{t1}^{t2} y\,dt \quad \text{where } y = q_m \quad \text{(I/1.1.2-3)}$$

for totalized mass

Now with this introductory discussion complete, it is time to go deeper into the systems and to define a few terms and their requirements, starting by exploring compressibility and noncompressibility.

4. **Compressibility and noncompressibility:** Compressibility of any substance is the measure of its change in volume under the action of external forces, e.g., due to pressure as shown in Fig. I/1.1.2-4. It is the fractional change in

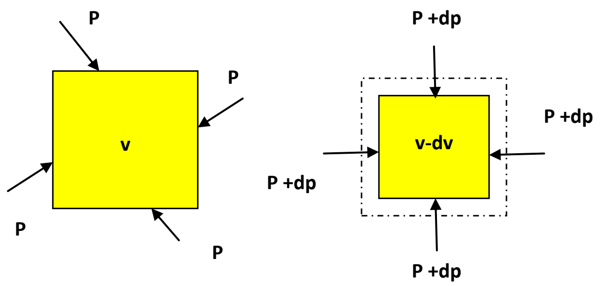


FIGURE I/1.1.2-4 Compressibility of fluid.

volume of fluid on account of unit change in pressure. Now let us look at this issue from a density point of view. On application of pressure when there is negligible or no variation in density in the flow domain, this is an incompressible fluid. Of course, there will be some variation of density with temperature (as there will be change of volume due to temperature). Obviously, this is true for liquids. On the other hand, compressible fluid flow defines "variable density flow" [6].

Combining the two aspects together for perfect gas the following equation holds good. If ρ = density; P = operating pressure, and T = operating temperature in Kelvin

$$P = \rho RT; \qquad (I/1.1.2\text{-}4)$$

where R is the gas constant variable with gas and is given by $R = \bar{R}/M$ where $\bar{R}$ is the universal gas constant 8314 J/kg·K. Like pressure and temperature, heat and energy are important issues. Therefore, it is necessary to look at them calorically. In order to limit this discussion, details of thermodynamics are not covered and readers are advised to consult any standard book on thermodynamics. Here only relevant details are discussed.

Specific heat at constant pressure C_p and specific heat at constant volume C_v are related by the following equation

$$C_p - C_v = R; \text{ specific heat ratio } \Upsilon \text{ (or Kappa } \kappa \text{ sometimes used)} = C_p/C_v; \qquad (I/1.1.2\text{-}5)$$

so that,

$$C_p = \frac{\Upsilon R}{\Upsilon - 1} \quad C_v = \frac{\Upsilon}{\Upsilon - 1} \qquad (I/1.1.2\text{-}6)$$

Eqs. I/1.1.2-5 and I/1.1.2-6 are very relevant for flow element sizing. Now applying the first and second laws of thermodynamics one finally arrives at the isentropic relationship given by

$$(P_2/P_1) = (\rho_2/\rho_1)^{\Upsilon} = (T_2/T_1)^{(\Upsilon/\Upsilon-1)}; \qquad (I/1.1.2\text{-}7)$$

Eq. (I/1.1.2-7) has been established to show the relationship of density, which has a direct impact on flow measurement, with a variation in pressure and temperature in the isentropic process. In the isentropic process, entropy is constant and the process is reversible and adiabatic (consult any standard book on thermodynamics). Another important parameter is the Mach number, which is the ratio of local velocity (V) to the speed of sound (c), i.e.,

$$M = \frac{V}{c}; \qquad (I/1.1.2\text{-}8)$$

If $M < 0.3$ it is subsonic incompressible and if $0.3 < M < 0.8$ it is subsonic compressible flow. $M < 1$ is subsonic flow and $M > 1$ is supersonic flow. So from here one gets to know that *significant velocity change, pressure, and temperature give variations in fluid density* in compressible fluids. Compressibility (k) is a reciprocal of the bulk modulus of elasticity (E) and compressibility can also be defined as

$$k = \frac{1}{\rho}\frac{d\rho}{dp} \quad \text{i.e. } d\rho = \rho k dp; \qquad (I/1.1.2\text{-}9)$$

There are two types of compressibility, namely, isothermal compressibility k_T and isentropic compressibility k_S. k and E depend on the nature of the process. From Mach number one can define transonic (0.8 < M > 1

or 1.2) and supersonic shock waves (1 or $1.2 < M < 3$). These are stated here because compressible fluid has an important impact on flow such as: choked flow is flow in a closed pipe/duct that is limited by sonic condition. A pressure ratio of 2:1 can cause sonic flow.

Noncompressible fluid: if the flow velocity is small compared to the local acoustic velocity, the compressibility of gases can be neglected. Considering a maximum relative change in density of 5% as the criterion of an incompressible flow, the upper limit of Mach number becomes approximately 0.33 [7].

5. **Non-Newtonian and Newtonian flow:** At the start of Section 1.1.2 it was stated that density and viscosity have an immense impact on fluid flow. From Subsection 1.1.2.4 it has been established that a variation in density actually divides fluid into noncompressible and compressible fluids. It has been observed that flow velocity is also an influencing factor. From the kinetic theory of gas it is established that molecular velocity gives rise to pressure and hence affects density.

$$PV = 1/3\ Nmc_{rms}^2; \qquad (I/1.1.2\text{-}10)$$

where P = pressure; V = volume, N = number of molecules c_{rms} = RMS velocity; m = molecular mass.

Amongst the various materials available around the world, there are wide variations in viscosity, e.g., when air has viscosity in the order of 10^{-5} viscosity units, molten glass has viscosity in the order of 10^{12} of the same viscosity units [8]. As viscosity goes on increasing, the fluid tends to become a solid (e.g., glue). So, for argument sake, one can consider a solid as a fluid with viscosity tending towards infinity. This stands to signify that as viscosity increases materials loses their flowability. Similarly, viscosity is another impacting factor which divides fluids into Newtonian and non-Newtonian fluids depending on variations in viscosity (at constant temperature) with shear force normally encountered in, e.g., a pump. This is clear from Fig. I/1.1.2-5.

Newtonian fluids behave according to Newtonian law; shear stress is linearly proportional to the velocity gradient or rate of shear strain. So, if shearing stress is τ, and μ is dynamic viscosity, then

$$\tau = \mu \frac{dc}{dy}; \qquad (I/1.1.2\text{-}11)$$

Thus, for Newtonian fluids, the plot of shear stress against velocity gradient is a straight line through the origin. On the other hand, for non-Newtonian fluids, Eq. I/1.1.2-11 is not valid. On account of the fact that they do not follow the linear relationship of Newtonian law of viscosity these fluids are referred to as non-Newtonian fluids, e.g., major polymers, adhesives, and ketchup, to name a few that show non-Newtonian fluid behavior. *A detailed account for Newtonian and non-Newtonian fluids is presented in Section 1.0.0 of Chapter VII.*

- *Newtonian fluid:* From Fig. I/1.1.2-6 it can be seen that in the case of Newtonian fluids there is a linear relationship between stress and strain. This is because Newtonian fluids viscosity remains unchanged at constant temperature, no matter the amount of shear applied. Also, in Newtonian fluids viscosity is independent of shear rate. This has been very clearly shown in Fig. I/1.1.2-5.
- *Non-Newtonian fluid:* As is seen in Fig. I/1.1.2-6, in a non-Newtonian fluid, the relationship between the shear stress and the strain rate is nonlinear, and it can even be time-dependent also. Therefore, a constant coefficient of viscosity cannot be defined.

  From Fig. I/1.1.2-6 it can be seen that there are two kinds of nonlinear curves, for two types of non-Newtonian fluids. These cases are described below.
  - Dilatant: In this case viscosity increases with shear stress, hence $n > 1$, e.g., quicksand. These are also termed as shear-thickening.
  - Pseudoplastic: In this case viscosity decreases with shear stress, hence $n < 1$, e.g., ketchup.

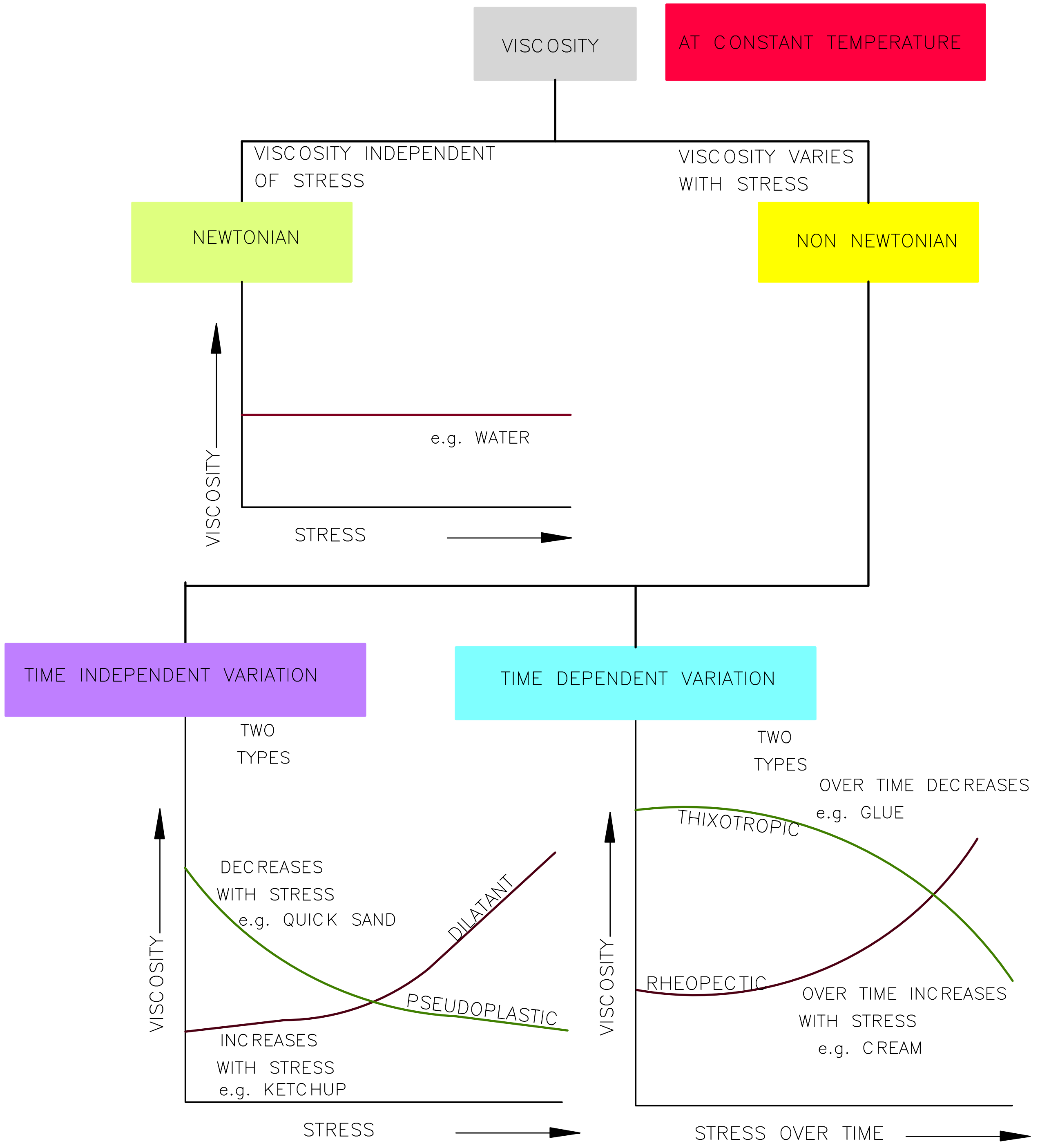


FIGURE I/1.1.2-5 Non-Newtonian and Newtonian flow types.

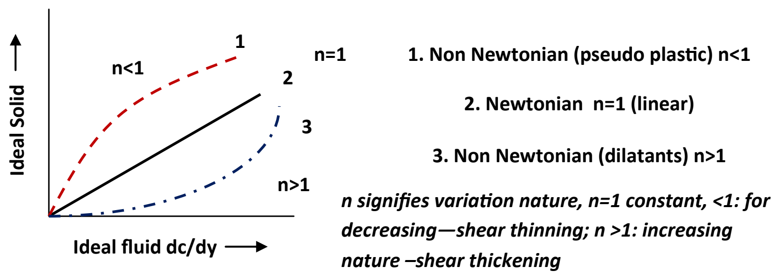


FIGURE I/1.1.2-6 Stress–strain relationship for fluid types. *Based on an idea from Fluid Mechanics, IIT Kanpur, http://nptel.ac.in/courses/112104118/lecture-1/1-11-cause-of-viscosity.htm#DemoCausesofViscosity.*

The above two cases of non-Newtonian fluids are cases where the change in viscosity is independent of time as shown in Fig. I/1.1.2-5. However, there are cases where it is dependent on time, e.g., glue. Time-dependent variations in viscosity with stress also have two categories, as shown in Fig. I/1.1.2-5, and these are described here.

- Rheopectic: Like dilatant ($n > 1$), in rheopectic fluids viscosity increases with stress but is time-dependent, e.g., cream, gypsum.
- Thixotropic: Fluids with thixotropic properties decrease ($n < 1$) in viscosity when shear is applied, but this is time-dependent, e.g., glue, paint.

For a non-Newtonian fluid, the viscosity is determined by the flow characteristics. This has been depicted in Fig. I/1.1.2-7 for a velocity profile showing how various types change the profile. Fig. I/1.1.2-1 shows the velocity profile for a particular fluid, whereas in Fig. I/1.1.2-7 variations in velocity for different types of fluid have been highlighted to show how, with a change in fluid type, the velocity profile changes. Discussions on non-Newtonian and Newtonian fluid types are now concluded and we now look at change of flow types with Reynolds number mainly for Newtonian fluids. Discussions of the same for non Newtonian fluid has been covered in chapter VII.

6. **Fluid flow types and Reynolds number:** Osborne Reynolds is considered as the pioneer in investigating the variations in flow types. In Subsections 1.1.2.1 and 1.1.2.2 short discussions about the physical significance of dynamic viscosity and Reynolds number have been established. The Reynolds number (in Eq. I/1.1.2.2-1 or Eq. I/1.1.2.2-2 for a circular pipe) is primarily responsible for classifying various flow types.

So, we get $\mathbf{Re = \rho v d/\mu}$ (for meaning of symbols Eq. I/1.1.2.2-2 should be referenced).

Irrespective of the pipe diameter, type of fluid, or velocity based on Reynolds number fluid flows can be classified as [5]:

laminar flow for: **Re < 2300**; (Re_{Cr})
transitional flow for: **Re = 2300−4000**;
turbulent flow for: **Re > 4000**.

From the foregoing it can be seen that, in addition to viscosity, Re is also dependent on density. For liquids (incompressible), the density varies with temperature. However, for gases, the density depends strongly on the temperature and pressure.

- *Laminar flow:* Laminar flow is normally encountered when dealing with a small pipe and low flow velocity. In laminar flow, fluids flow in parallel layers without mixing [9]. This means that the fluid particles move in well-ordered adjacent sliding layers. The velocity distribution shows that

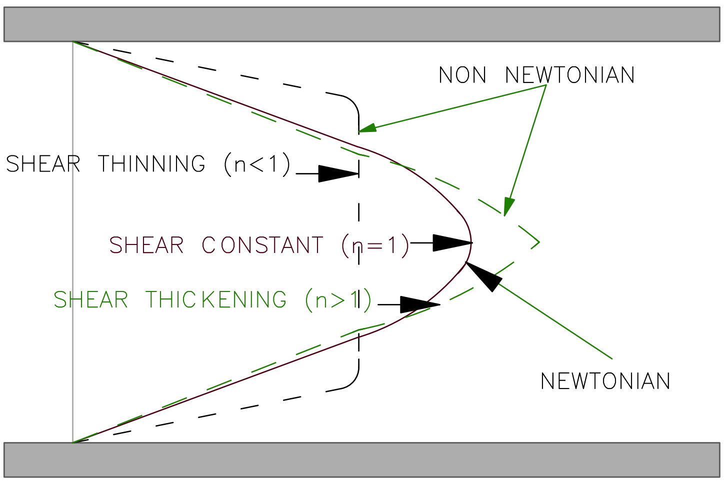


FIGURE I/1.1.2-7 Velocity profile for fluid types.

the frictional forces at the stationary pipe wall exert the highest retarding force and that from layer to layer the velocity increases to its maximum value, at the middle of the pipe [1]. At low velocities and high viscosities the fluid flows in layers, this is known as *laminar* flow in which the layers do not mix with one another. This is well depicted in Fig. I/1.1.2-8A with velocity profile. There are two types of laminar flow: (1) stable laminar flow (stable against imposed external disturbance) and (2) unstable laminar flow (when imposed external disturbance is amplified).

- *Turbulent flow:* Turbulent flow is noticed in high flow or in large pipe flow for Re > 4000. Since Reynolds number (Re) takes into consideration the essential factors, velocity v and viscosity ν (nu), so, it is an evaluation criterion. When the velocity increases or the viscosity decreases an additional motion is superimposed on the axially oriented movement throughout the flow stream. Flow vortices, wakes, and eddies make the flow unpredictable and cause movements in all directions in a random manner and affect the flow streamlines in such a way that there is a uniform velocity profile. However, at the wall or nearby, a boundary layer is formed on account of its adhesion to the wall. Therefore, the velocity must accelerate from zero to u. Thus, the velocity profile in the outer region is not steady. This is very clearly depicted in Fig. I/1.1.2-8B. Turbulent flow is characterized by rapid mixing and cross-currents flow perpendicular to the direction of motion and three-dimensionality [10].

Having gathered some knowledge on the two main types of flow, it is better to compare them to observe their changes. For this Table I/1.1.2-1 gives a comparison of laminar flow and turbulent flow.

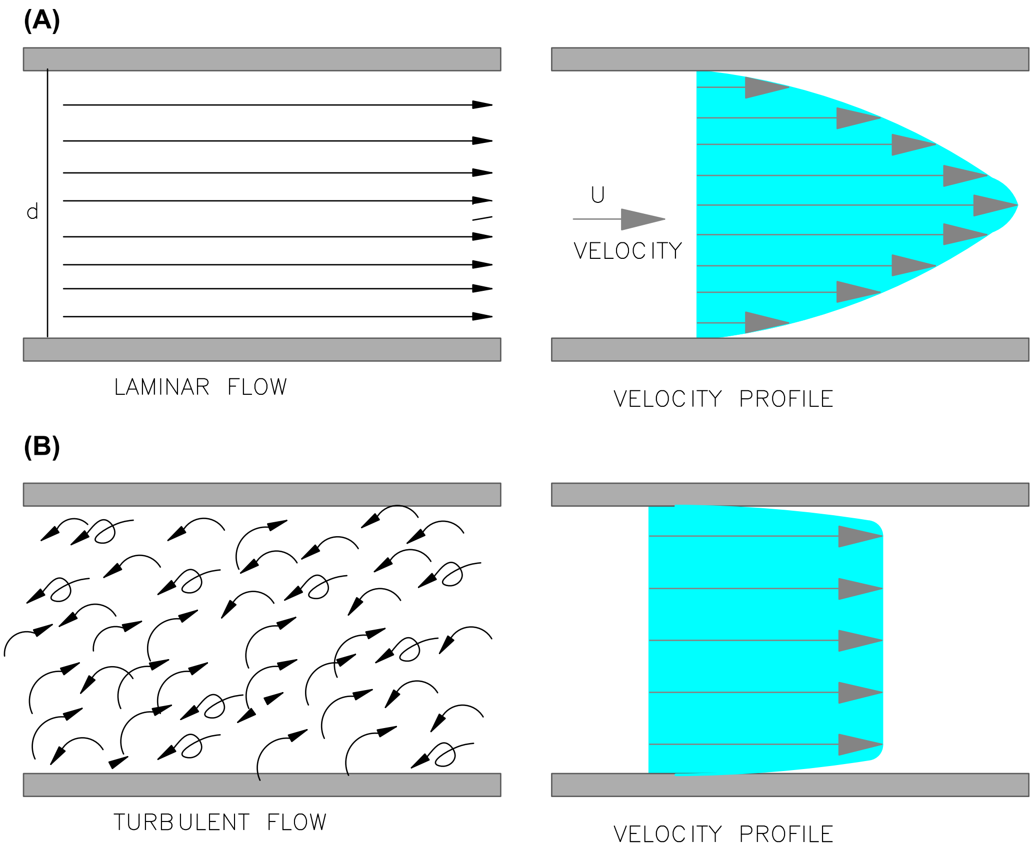


FIGURE I/1.1.2-8 Flow types and velocity profile. (A) Laminar flow and velocity profile. (B) Turbulent flow and velocity profile.

TABLE I/1.1.2-1 Comparison of Laminar and Turbulent Flow

Point of Comparison	Laminar Flow	Turbulent Flow
Reynold's number	Re < 2300	Re > 4000
Velocity profile	Parabolic (Fig. I/1.1.2–8A)	~Rectangular (Fig. I/1.1.2–8A)
Pressure drop	Small	Appreciable due to friction
Average velocity (v_{avg})	v_{avg} = 0.5 max. velocity v_{max} (wide variation)	v_{avg} = 0.5 max. velocity v_{max} (less variations)

- *Transitional flow:* Reynolds number **2300** is also referred to as the critical Reynolds number. **2300** (Re_{Cr}) is very important as from this point there is the probability of mixing, i.e., the critical Reynolds number 2300: Re_{Cr} defines with reasonable accuracy the transition point. Transitional flow is the mixture of the two above types of flow with the center being turbulent and the edges laminar.

7. **Various media flow measurement:** Fluid flow measurement in multiphase and slurry applications needs special attention on account of the complexity in flow measurements in these applications. Again, solid flow measurement is quite different from fluid flow measurement.
   - *Slurry flow:* Slurry flows are very important for mineral, metallurgical, pulp and paper, and food process engineering. The material transport in these plants takes place as slurry and/or complex fluids (commonly encountered in food and beverage industries e.g. Mayonnaise/chocolate). The most important characteristics of slurries are defined by their rheology described in Fig. I/1.1.2-9, which actually explains the nature of flow of matter. For any basic system design it is essential to understand the rheology of slurries. For further discussions on the same Section 3.3.0 in this chapter & Chapter VII may be referenced.
   - Solid flow measurements in dynamically feeding bulk materials (namely, clinker, raw meal, or fine materials) need a few considerations to attain high-accuracy measurements. There are a few "weighing basics" that allow for extremely sensitive and reliable recognition for both material load and belt speed—the two fundamental

Rheology: ***The term first was coined way back in 1920 Keeping in mind Greek quotation "panta rei" meaning everything flows. By definition, Rheology is a branch of physics and engineering which deals with the deformation and flow of matter, especially the non Newtonian fluids and plastic flow of solids. It is concerned with study of flow of matter mainly liquids, but also soft solids, solids which flows rather than deform. In real life application Rheology is concerned with applying and extending classical discipline of Elasticity and Newtonian fluid mechanics to special materials whose behavior cannot be described with classical theory.***

FIGURE I/1.1.2-9 Rheology.

measurements to provide accurate and repeatable gravimetric feeding [11].

The following are major issues necessary to be considered for having a high-performance (high accuracy and repeatability) systems such as weigh feeder.

- Minimal belt reaction error: This is a function of the belt; associated issues include the amount of inherent belt tension and the alignment of the weigh suspension.
- Efficient scale design: This is to ensure the proper transfer of the load sensed by the weigh suspension to the load reaction device.
- A high-performance load reaction device: These are the transducers that transform the sensed material load to a digital signal for the feeder's control system. Overall system accuracy and repeatability require that the speed determination be of a reliable source and of sufficient resolution as well as the weighing measurement issues discussed. There are several ways and means for solid flow measurements, a major few major systems have been listed below.
- Platform scale.
- Hopper weighing system.
- Belt scale/belt weigher.
- Weigh feeder.
- Impact scale.
- Loss in weight method.
- Batch system.
- Filling machines.
- Nucleonic system.

In most (with the exception of noncontact types) of the cases of solid flow measurements, mechanical construction and mechanical arrangements are very important. In fluid flow measurements, in most cases the measuring instrument (may be with associated control) is a self-contained unit. In solid flow measurements mechanical feeding arrangements are a major part of the measurements where instrument sensors with control systems carry out flow computation. So, in those cases close coordination with mechanical/process engineers is essential for accurate results. For detailed discussions Chapter VIII may be referenced.

- *Multiphase flow:* A multiphase flow measurement is the measurement of flow of each of different components found in a mixed form—especially oil, water, and gas. This measurement is a complex phenomenon producing a variety of flow regimes whose distributions, in both space and time, differ from each other [5]. There are mainly three variations in flow regimes, i.e., bubble type, stratified type, and slug type, as shown in Fig. I/1.1.2-10. The major use of multiphase flow measurements is in oil and gas area. There is a wide variety of instruments, starting from conventional DP type measurement to sophisticated instruments like Neuron and X-ray CT (computerized tomography) available for such measurements. Chapter IX is dedicated to multiphase flow measurements.

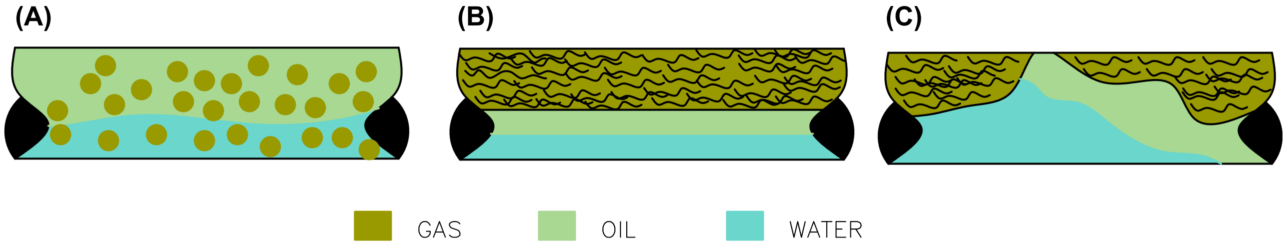


FIGURE I/1.1.2-10 Multiphase flow types. (A) Bubble type. (B) Stratified type. (C) Slug type.

1.2.0 General Relevant Terms and Discussions

In the above discussions, some relevant factors which influence flow measurements have been discussed in terms of their physical significance which will be helpful for understanding flow measurements. After completing short discussions on over view of flow measurement from this point onwards detailed discussion on flow measurement systems shall be discussed. These terms and some others are now looked at in more detail.

1.2.1 IMPORTANT TERMS RELATED TO INSTRUMENTATION

A few relevant terms for flow measurements and flow-measuring instruments are discussed in this subsection. These are relevant for instruments their selection of instruments.

1. **Accuracy and accuracy measurement:** The dictionary definition of accuracy is “freedom from error.” However the ISA defines accuracy as “In process instrumentation, degree of conformity of an indicated value to a recognized accepted standard value, or ideal value.” Also, as per ISA, it is measured in terms of positive and negative deviations observed during testing under specified conditions and procedures. According to B.G. Liptak “When an instrument is specified to have ±1% accuracy, people do not expect it to have 99% error! The intended meaning of that statement is ±1% inaccuracy or a ±1% error relative to some reference standard” [12]. According to ASME, the “accuracy” of flow measurement is the degree of freedom from error, or the degree of conformity of the indicated value of the instrument to the true value of the measured quantity [13].
2. **Accuracy discussions:** One important criterion in flow meter selection is ***accuracy***, which highly depends on the turndown (TD) ratio. However, installation, e.g., straight length, plays a role in attending accuracy in flow measurement. Often people specify accuracy in terms of % of full-scale division (FSD), often also referred to as full scale (FS). Also, it is quite common to specify accuracy in terms of percent of actual reading (AR). In connection with this, Fig. I/1.2.1-1 may be

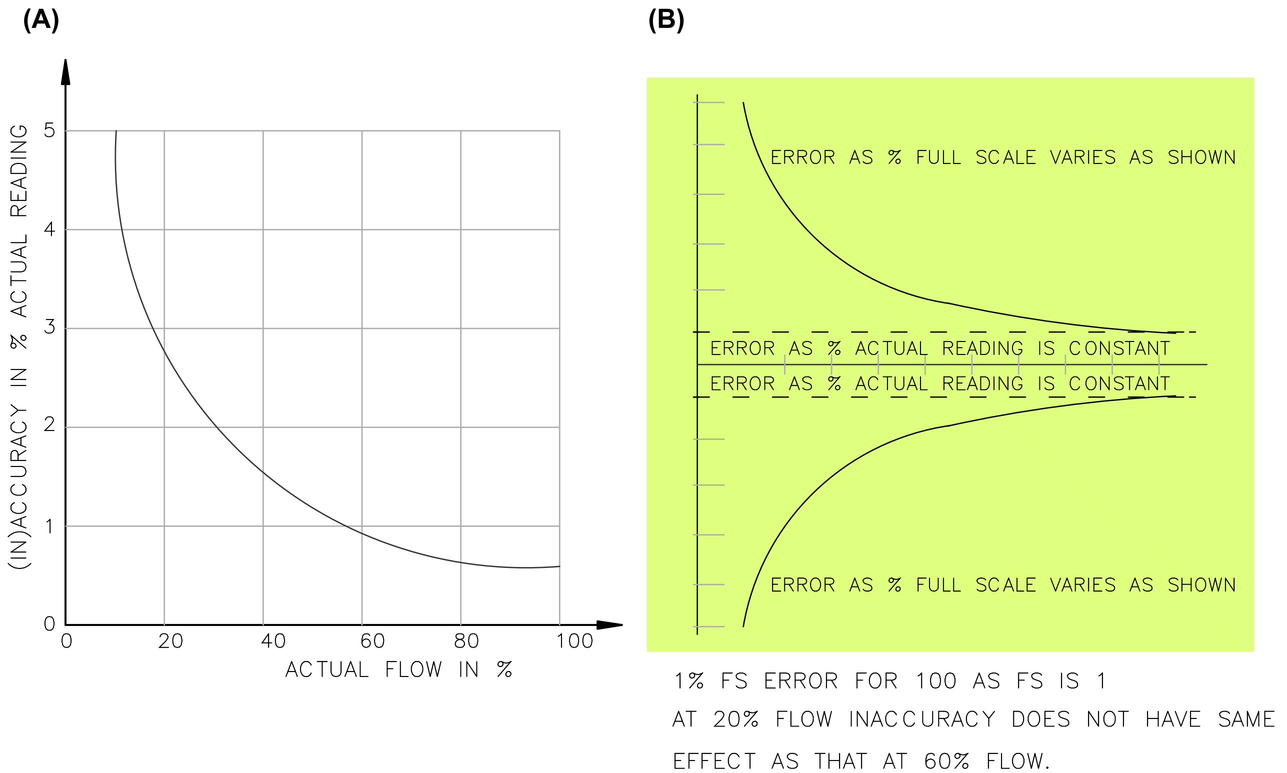


FIGURE I/1.2.1-1 Error and performance of measurement. (A) Error in terms of % actual reading. (B) Error as full scale and actual reading.

referenced. As FS is always larger than the calibrated span (CS), a sensor with percent FS performance will be less accurate than one with the same percent CS specification, e.g., an instrument with a range of, e.g., 1000 units and a calibration span of 500. Therefore, 1% FSD will be a 10-unit error but for 1% CS, the error will be 5 units. So, for comparison, it is advisable to convert all quoted accuracies in terms of percent of AR units [14]. The issue will be clear from an example. Suppose a meter has a full scale of 100 units. Therefore, an accuracy of 1% FSD means that the error will be 1 unit. Now when the actual flow is 20 units it may show 19 or 21 units. Similarly at 80-unit flow it may show 79 or 81 units. Naturally, the effects of such an error at 20% and 80% are not same. In contrast, a 1% reading has a constant impact at all flow ranges. This has been shown in detail in Fig. I/1.2.1-1B. Also refer to Subsection 1.2.1.5 below for guaranteed accuracy.

3. **Error and uncertainty:** According to ISA it is the algebraic difference between the indication and the ideal value of the measured signal and can be obtained by making an algebraic difference between the two values. The uncertainty of a measurement represents the doubt about the validity of the result of the measurement. This is related to the instrument calibration system. From ASME one gets "uncertainty of measurement" as the range within which the true value of a measured quantity can be expected to lie with a specified probability and confidence level [13].
4. **Range:** According to ISA it is the two extreme limits within which a quantity is measured, received, or transmitted. This is expressed specifying the upper range limit (URL) and the lower range limit (LRL).
5. **Rangeability/turndown:** Rangeability is also commonly referred to as the turndown ratio or span ratio. Though it is described as rangeability, this is in terms of the span of the instrument. It indicates the span in which a flow meter or controller can accurately measure the fluid. In other words, it's simply the high end of a measurement span compared to the low end of measuring span, expressed in a ratio of maximum flow:minimum flow, e.g., if a given flow meter has a 50:1 turndown ratio the flow meter is capable of accurately measuring down a 1/50th of the maximum flow. There lies the fallacy, suppose an instrument is specified as having an overall accuracy of 0.075% FSD accuracy and turndown ratio of 400:1. What does this mean? This means that for this instrument you can set a span of, e.g., 0−1 kg/cm^2, or you can even set the instrument as a 0−400 kg/cm^2 span. However, the maximum accuracy is also available as 0.075% FSD. However, it NEVER specifies that both happen at the same time. For this reason, manufacturers provide the accuracy variation curve. This is similar to the *guaranteed accuracy that may be achievable for a TD of, e.g., 6:1.*
6. **Repeatability:** As per ISA it is the closeness of agreement among a number of consecutive measurements for the same value of the input under the same operating conditions, approaching from the *same* direction, for full-range traverses. Another term often encountered is "***reproducibility***," which is similar except that in this case the approach is from *both* directions. In this connection, the ASME definition may be interesting. According to ASME, "**repeatability**" for flow measurement is the closeness of agreement among a series of results obtained with the same method on identical test material, under the same conditions (same operator, same apparatus, same laboratory, and short intervals of time), whereas "reproducibility" for flow measurement is the closeness of agreement between results obtained when the conditions of measurement differ, e.g., with different test apparatus [13].

7. **Span:** Span can be defined as the algebraic difference between the upper- and lower-scale values within which the instrument is supposed (or calibrated) to work. Normally, for instruments, the minimum and maximum spans are specified. This indicates that one cannot calibrate the instrument lower than the minimum span (0.05kPa i.e. Kilo Pascal) and or more than the maximum span (max value of URL 1kPa). However, within these span limits any span can be selected and can be set at any point within the range as shown in Fig. I/1.2.1-2 with suitable example.
8. **Range:** This can be defined as the lowest and highest readings the instrument can measure. Therefore, range refers to the capability of the instrument. Normally, the lower range limit (LRL) and upper range limit (URL) are specified, e.g., an instrument (say one DP transmitter, e.g., 265DS of ABB) with a range ±1 kPa means it can measure LRL = −1 kPa and URL = 1 kPa (refer to Fig. I/1.2.1-2).
9. **Linearity:** Linearity is a measure of the proportionality between the actual process variable (being measured) values to the instrument output within the calibrated span. In the case of flow measurement by a rotameter it is linear but for a head type measurement with the help of a differential pressure (DP) transmitter (DPT) it is nonlinear.
10. **Drift:** Drift is the change in the reading of an instrument of a fixed variable with time. There may also be drift due to temperature also.
11. **Hysteresis:** Hysteresis can be defined as the different readings noted when an instrument approaches a signal from opposite directions. This means that the path followed by instrument reading ascends from the lower to the upper range may not be the same when the same instrument reading descends from the upper to the lower range. There will be a gap which signifies hysteresis.
12. **Sensitivity:** The sensitivity of an instrument is the ratio between the *changes* in the output of an instrument to the corresponding *changes* in the measured variable. The higher the ratio, the greater will be the sensitivity of the instrument—a desirable feature of the instrument.
13. **Resolution:** This is the smallest difference in input (process) variable to which the instrument is capable of responding.
14. **Offset:** The offset of an instrument represents the reading of the instrument at zero input variable.
15. **Zero/span adjustment:** An instrument with an offset needs adjustment. Such an

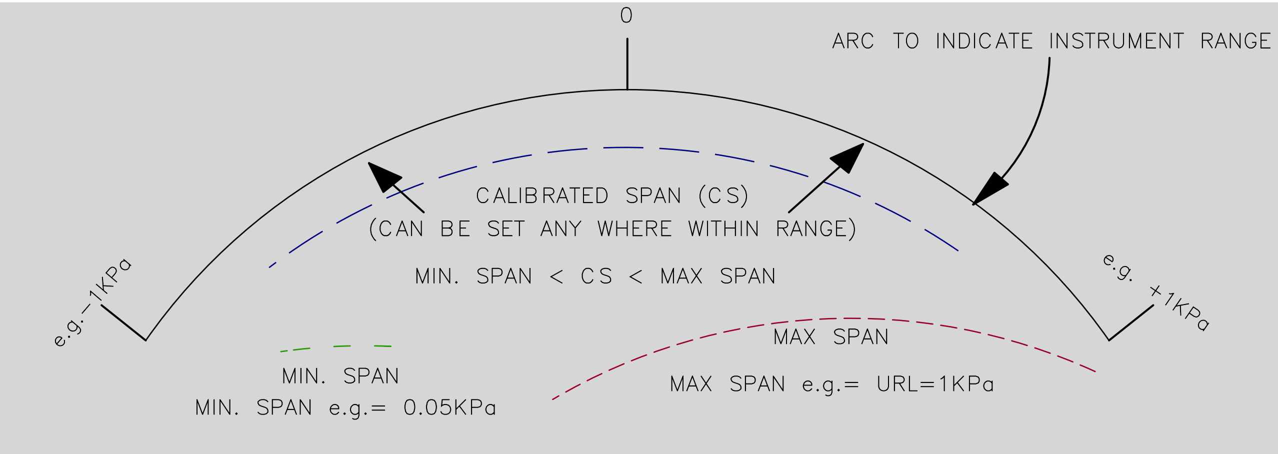


FIGURE I/1.2.1-2 Range and span of instrument.

adjustment is known as zero adjustment. Therefore, a change in zero is often called bias error or DC offset or *zero shift*. Any ideal linear device has the following relationship:

Output $Y_1 = m_1X + 0$; if the instrument responds as follows:

$Y_1 = m_2X + C$, then the instrument needs adjustment. The adjustment of setting C to zero is called zero adjustment. Meanwhile the adjustment m_2 to m_1 (i.e., of gain) is referred to as span adjustment. In this connection Fig. I/1.2.1-3 may be referenced.

From the above some idea of zero and span adjustments is gathered. For further details, Ref. [15] may be referred to. With this the discussions on instrument characteristics are concluded and we move on to understand how various physical parameters affect flow and their physical significance.

16. **Vector product:** It is known that of the various physical quantities a few are scalar, such as speed and work done, and a few are vector quantities, such as magnetic or electric field and velocity. When these physical entities interact with one another the products can also be scalar or vector quantities. It is known that each force and displacement is a vector quantity but work done, which is computed from force and displacements, is a scalar quantity. This is because in this case the dot (·) product of these two quantities is computed to get work done. On the other hand, in the case of voltage developed in an electromagnetic flow meter is computed by cross-product of fluid velocity and magnetic field (both vector quantity). So, in generalized way it can be:

for two vectors, namely, $\vec{\mathbf{a}}$ **and** $\vec{\mathbf{b}}$ **with angle θ** between them will have:

dot product: $\vec{\mathbf{a}} \cdot \vec{\mathbf{b}} = \mathbf{a \cdot b \cdot \cos\theta}$—this is a scalar quantity, whereas,

cross-product $\vec{\mathbf{a}} \times \vec{\mathbf{b}} = \mathbf{a \cdot b \cdot \sin\theta}$ (here the modulus of a, b should be used) and the direction of the resultant vector will be orthogonal to both $\vec{a}$ and $\vec{b}$. The direction will be obtained by the right-hand rule from a to b. Naturally the cross-product of $\vec{b} \times \vec{a}$ will not be same as $\vec{a} \times \vec{b}$ (the direction will be different).

1.2.2 TERMS RELATED TO THE PROCESS

Here a few terms already discussed and a few new terms and their relevance in measurements will be discussed.

1. **Hydraulic diameter (D_h):** characteristic length (in meters): The hydraulic diameter can be considered as the characteristic length used to calculate the Reynolds number (Re). In the case of a circular pipe (completely filled) it is the same as the diameter but in case of a noncircular pipe/duct it has a separate significance. This uses the perimeter and the area of the conduit to provide the diameter of a pipe which has proportions such

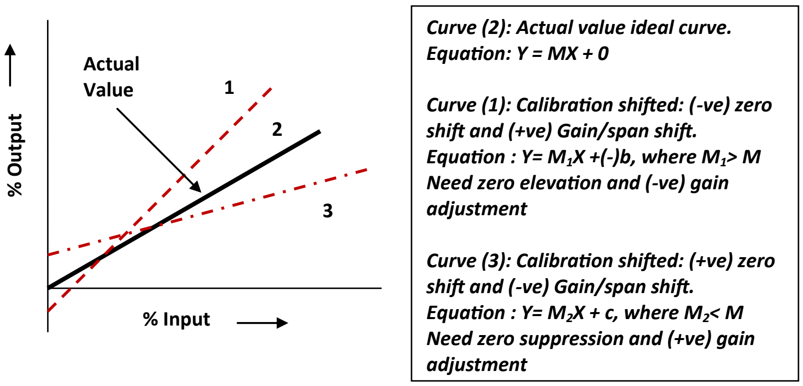


FIGURE I/1.2.1-3 Adjustment of instrument zero and span.

that the conservation of momentum is maintained. It is very useful in establishing the relationship between circular and noncircular pipes. It is very useful for *turbulent flow*, but is **not** applicable for *laminar flow*. When A is the cross-section area and P is the wetted perimeter (see Subsection 1.0.2.5 in Chapter III), hydraulic diameter for full flow is defined as

$$D_h = 4A/P \qquad (I/1.2.2\text{-}1)$$

Typical D_h for different geometry is shown in Fig. I/1.2.2-1 for a few shapes only.

2. **Viscosity:** The physical significance and phenomenon of viscosity have been discussed in Section 1.1.2 above. As already discussed, viscosity is the internal friction in a fluid. The viscosity of a fluid characterizes its ability to resist shape changes. So, the viscosity of a fluid is a measure of its resistance to gradual deformation by shear stress or tensile stress. As discussed earlier, the shear resistance in a fluid is caused by intermolecular friction exerted when layers of fluid attempt to slide by one another. Viscosity arises from the intermolecular force and provides resistance to shear force, and is highly dependent on temperature. In connection with this Section 1.1.2 and Fig. I/1.1.2-2 may be referenced. It is worth noting that the discussions put forward here are mainly

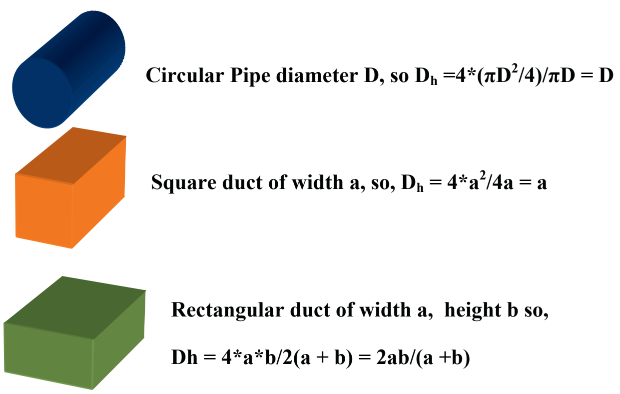


FIGURE I/1.2.2-1 Hydraulic diameter for different geometry (typical shapes only).

based on Newtonian fluids (n = 1) as shown in Fig. I/1.1.2-6. Discussions on this for non-Newtonian fluids are covered in Chapter VII. There are two related measures of fluid viscosity, these include the following.

- *Dynamic (or absolute) viscosity:* Dynamic (absolute) viscosity is the tangential force per unit area required to move one horizontal plane with respect to another plane—at a unit velocity—whilst maintaining a unit distance apart in the fluid. From Section 1.1.2 it has been seen that shear stress = μ·shear rate. So, dynamic viscosity can be expressed as:

$$\tau = \mu dc/dy \qquad (I/1.2.2\text{-}2)$$

Eq. (I/1.2.2-2) is termed as **Newton's law of friction** and is applicable for Newtonian fluids (n = 1) as shown in Fig. I/1.1.2-6, where, τ = shearing stress (N/m^2), μ = dynamic viscosity (N s/m^2), dc = unit velocity (m/s), dy = unit distance between layers (m) (to take care of dc with distance from center).

In the SI system the dynamic viscosity units are ***N s/m^2, Pa s*** or ***kg/(m s)***—where **1 Pa s = 1 N s/m^2 = 1 kg/(m s)**. In **CGS** *this is* g/(cm s), dyne s/cm^2 or poise (p) where **1 P = 1 dyne s/cm^2** = 1 g/(cm s) = 1/10 Pa s = 1/10 N s/m^2. Centipoise (cP) is often used where **1 cP = 1/100 P**. Typically, at ~20°C, water viscosity = 1 cP.

- *Kinematic viscosity:* The kinematic viscosity ν (nu) is a *density-related viscosity* and has units of m^2/s. It has the ratio of *absolute (or dynamic) viscosity to density*, a quantity independent of force.

So,

$$\nu(\text{nu}) = \mu/\rho \qquad (I/1.2.2\text{-}3)$$

where, ν = kinematic viscosity (m^2/s); μ = absolute or dynamic viscosity (N s/m^2) and ρ = density (kg/m^3). In SI, kinematic viscosity is in **m^2/s** or **Stoke (St),** where 1 **St (Stokes) = 10^{-4} m^2/s = 1 cm^2/s.**

Another practical unit is **Centistoke (cSt)**, where **1 cSt = 1/100 St = 1 mm²/s**.

The specific gravity for water at 20.2°C (68.4°F) is ~1 and the kinematic viscosity of water *at 20.2°C is ~1.0* mm²/s (*cStokes*) (1.0038 mm²/s [cStokes]).

Typical values of a few selected product are presented in Table I/1.2.2-1.

There is another way kinematic viscosity is expressed, i.e., SUS (mainly used in petroleum industries). For this Fig. I/1.2.2-2 may be referenced. Reynolds number is an important issue in determining types of flow as discussed in Subsection 1.1.2.6.

3. **Reynolds number:** The most prominent nondimensional parameter which emerges from flow analyses is the Reynolds number, named after Osborne Reynolds for his immense contribution to fluid mechanics. The Reynolds number can be defined as the ratio of the inertia force (ρvL), and the viscous or friction force (μ), i.e.,

$$Re = \frac{\rho v L}{\mu} \qquad \text{(I/1.2.2-4)}$$

By multiplying both the numerator and denominator by the (average) velocity v, one gets

$$Re = \left(\rho v^2 L\right)/\mu v \qquad \text{(I/1.2.2-5)}$$

So, it can be interpreted as the ratio of the dynamic pressure (ρv^2) and the shearing stress (μv/L). Here, Re = Reynolds number (nondimensional); ρ = density (kg/m³, lb_m/ft^3); v = velocity based on the actual cross-section area of the duct or pipe (m/s, ft/s); μ = dynamic viscosity (N s/m², lb_m/s ft); L = characteristic length (m, ft) in the case of a closed circular pipe it is d; ν(nu) = μ/ρ = kinematic viscosity (m²/s, ft²/s).

TABLE I/1.2.2-1 Absolute Viscosity Value (in cP) of a Few Selected Materials: Unless Stated Otherwise All the Values are at 20°C

Materials	Viscosity (cP)	Materials	Viscosity (cP)
Air-gas	0.018	Hydrogen gas	0.009
Ammonia gas	0.00982	Kerosene	10
Benzene	0.604	Ketchup	(50–100) × 10^3
Blood at 37°C	3–4	Light oil	1.1 × 10^2
Carbon dioxide gas	0.0148	Methanol	0.544
Carbon monoxide gas	0.01720	Molasses	(5–10) × 10^3
Ethane gas	0.0095	Molten chocolate	(45–130) × 10^3
Ethanol	1.074	Molten glass	(1–100) × 10^4
Ethyl alcohol	0.12	Motor oil SAE40	250–500
Gasoline	0.6	Nitrogen gas	0.01781
Heavy oil	6.6 × 10^2	Oxygen gas	0.020
Helium gas	0.019	Steam at 100°C	0.013
HFO380	>2000	Sulfur dioxide gas	0.01254
Honey	(2–10) × 10^3	Water	0.894

Saybolt universal Second (SUS) is an alternative unit for measuring Kinematic viscosity in classical mechanics. It is a measure of time required for 60 milliliter of petroleum product to flow through the calibrated orifice of a Saybolt universal viscometer, under controlled temperature and conditions prescribed by test method ASTM D 88. Relation between Kinematic viscosity in SSU and absolute viscosity can be expressed *as:*

$\nu_{SSU} = B\,\mu / Sp\ gr.$ Or $\nu_{SSU} = B\nu_{centistokes}$; where sp gr. Is the specific gravity, ν_{SSU} = kinematic viscosity (SSU);

μ = dynamic or absolute viscosity (cP). B varies with temperature;

B = 4.632 & 4.664 at 1 00 °F (37.8 °C) & 210°F (98.9 °C)respectively.

FIGURE I/1.2.2-2 Saybolt universal second for kinetic viscosity.

For a pipe or duct, the characteristic length is the hydraulic diameter. $L = d_h$, where, d_h = hydraulic diameter (m, ft) (see Subsection 1.2.2.1).

The Reynolds number for a duct or pipe can be expressed as

$$\begin{aligned} Re &= \rho v d_h/\mu = v d_h/\nu \\ &= (\text{for circular pipe it is } vd/\nu) \end{aligned} \tag{I/1.2.2-6}$$

So, this inertial force and viscous force ratio consequently give relative importance to two types of force. When the viscous force is relatively more important, and disturbances in the flow are damped out by viscosity, there will be relatively low values of Reynolds number. Thus, it is difficult for disturbances to grow and sustain themselves. On the other hand, at relatively large values of Reynolds number, the damping of disturbances by viscosity is less effective, and inertia is more important, so that disturbances can perpetuate themselves. This is the basic reason why the Reynolds number serves as a measure for determining whether the flow is laminar or turbulent [16]. From the above discussions it is also clear that the transition from laminar to turbulent flow depends on the geometry, surface roughness, flow velocity, surface temperature, and type of fluid, among other things.

4. **Average velocity:** From Fig. I/1.1.2-1, it can be seen that as one moves from the center of the pipe the velocity values change. The fluid velocity in a pipe changes from zero at the surface because of the no-slip condition to a maximum at the pipe center. In fluid flow, it is convenient to work with an average velocity, v_{avg}, which remains constant in incompressible flow when the cross-sectional area of the pipe is constant, as shown in Fig. I/1.2.2-3. The average velocity for compressible fluid and heating and cooling applications may change somewhat on account of changes in density with

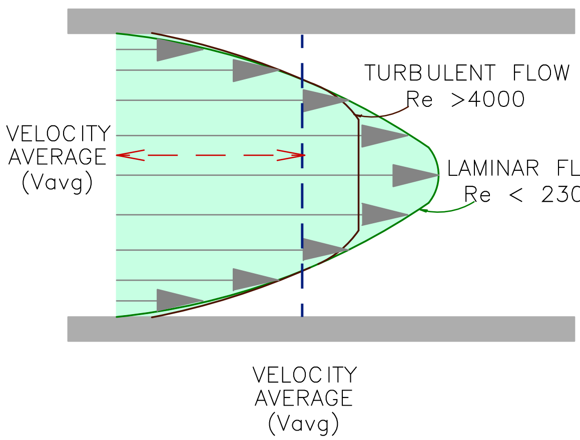


FIGURE I/1.2.2-3 Flow types and average velocity.

temperature. However, for convenience, in practice, the fluid properties at some average temperature are evaluated and are considered as constants. The convenience of working with constant properties in most cases is usually more justifiable than slight loss in accuracy in measurement. There may be a slight change in temperature due to friction (some sensible heat) but it is not noticeable, and the pressure drop is prominent.

By applying conservation of mass principle, it is possible to calculate the average velocity in the following manner. If "q_m" is the mass flow rate, "ρ" is the density of the medium, "A" is the cross-section of a circular pipe, and v_{avg} is the average velocity, then one can say:

$$q_m = \rho \cdot A \cdot v_{avg} \qquad \text{(I/1.2.2-7)}$$

Now, when a small section of velocity profile variations across a radius represented by v(r) is taken and integrated over the area, then

$$q_m = \rho \cdot A \cdot v_{avg} = \rho \int_0^A v(r)dA \text{ or, } v_{avg} = \left(\rho \int_0^A v(r)dA\right) \Big/ (\rho A) \qquad \text{(I/1.2.2-8)}$$

Putting the parameters pertinent to the closed circular pipe one gets:

$$v_{avg} = \left(2\pi\rho \int_0^R v(r)rdr\right) \Big/ (\rho\pi R^2) = \left(\frac{2}{R^2}\right) \int_0^r r \cdot v(r)dr \qquad \text{(I/1.2.2-9)}$$

Therefore it is possible to calculate v_{avg} when the velocity profile/flow rate is known for noncompressible fluid. For compressible fluid density, variations need to be considered.

5. **Pipe, tube, duct, and conduit:** The terms pipe, tube, duct, and conduit are usually used interchangeably for flow sections (Fig. I/1.2.2-4). In general, flow sections of circular cross-section are referred to as *pipes* (especially for liquid), and flow sections of noncircular cross-section as *ducts* (especially for gas). Small-diameter pipes are usually referred to as *tubes. Pipes are normally specified by nominal bore (NB) (or DN as per Din standard) and schedule. Corresponding to each nominal bore has one unique outer diameter while the thickness is governed by schedule.*

It is noticed that normally a circular pipe is chosen for fluid flow, especially for

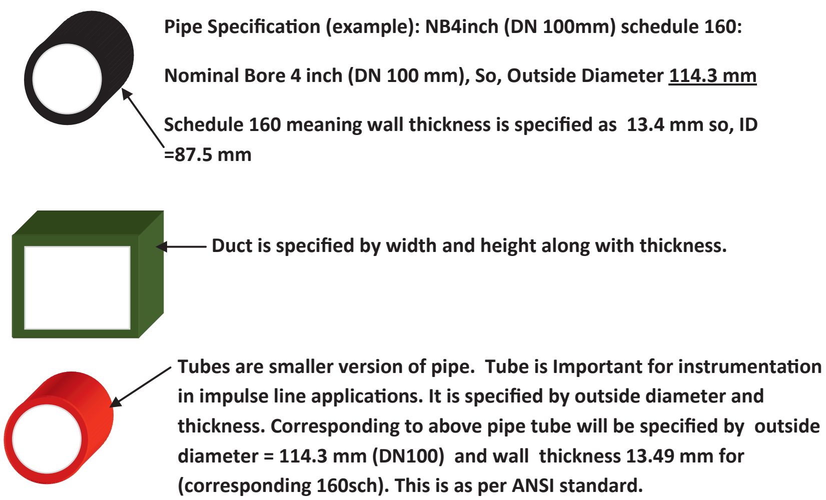


FIGURE I/1.2.2-4 Pipe duct and tube as fluid flow sections.

high-pressure services and when liquids and steam are used. *Why?* This is because pipes with a circular cross-section can withstand large pressure differences between the inside and the outside without undergoing significant distortion. On the other hand, ducts are chosen for fluid flows like gases and air on account of their low-pressure application, space requirements for corresponding volume, and costs. Tubes are chosen for certain special applications.

6. **Flow separation and velocity profile disturbance:** At the boundary wall of the circular pipe there exists a boundary layer in which the flow velocity increases from zero to v. So, when the obstruction is the wall, the boundary layer extends to restrain the fluid flow more in the vicinity of the wall. Thus, downstream of the aforesaid restriction, there exists a dead zone and even a slight negative pressure. Again due to the restriction, there will be acceleration, so the fluid flows from the region of *higher* velocity into this dead zone and creates **vortices**. The flow separates from the surface of the wall as depicted in Fig. I/1.2.2-5. In Fig. I/1.2.2-5A acceleration, restraining, and vortex formation are shown, while in Fig. I/1.2.2-5B flow separations have been depicted for two different cases. These vortices consume energy and account for some loss. They also change the velocity

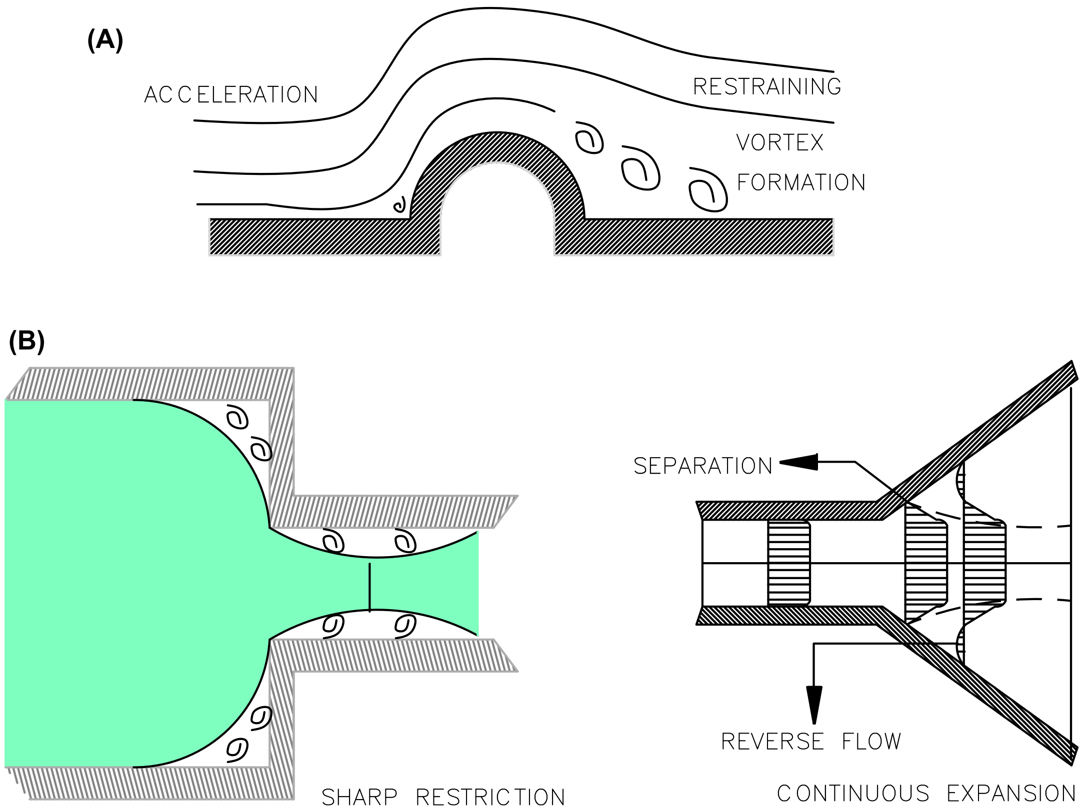


FIGURE I/1.2.2-5 Flow separation phenomenon. (A) Dead zone and vortex formations. (B) Flow separation and profile. *Based on an idea from F. Frenzel, H. Grothey, C. Habersetzer, M. Hiatt, W. Hogrefe, M. Kirchner, G. Lütkepohl, W. Marchewka, U. Mecke, M. Ohm, F. Otto, K.-H. Rackebrandt, D. Sievert, A. Thöne, H.-J. Wegener, F. Buhl, C. Koch, Deppe, E. Horlebein, A. Schüssler, U. Pohl, B. Jung, H. Lawrence, F. Lohrengel, G. Rasche, S. Pagano, A. Kaiser, T. Mutongo, Industrial Flow Measurement Basics and Practice, ABB Automation Products GmbH, http://nfogm.no/wp-content/uploads/2015/04/Industrial-Flow-Measurement_Basics-and-Practice.pdf.*

profile and in some cases these are not desirable for measurement.

Similarly obstructions in the flow conduit (closed circular pipe) like bends, elbows, reducers, expanders, strainers, and control valves—to name a few—also affect flow profile greatly and so affect the flow measurement. Finally, the flow profile can be restored by the natural mixing action of the fluid particles as the fluid moves through the pipe for a greater distance. This is the main reason that the upstream and downstream straight lengths are specified. Typical such velocity profile disturbance and restoration inside the closed circular pipe are detailed in Fig. I/1.2.2-6.

Such flow disturbance should never be confused with turbulence which occurs due to the Reynolds number (Re). In fact, when bearing in mind the first part of the discussion in this subsection, one may note that such a disturbance will give rise to an *asymmetrical* velocity profile and the following interesting phenomena.

- *Vortex:* Areas of swirling motion with high local velocity which are often caused by separation or a sudden enlargement in the pipe area as shown in Fig. I/1.2.2-5. When a body is placed in the middle of a media flow with the Re above a certain value, separation occurs and vortices are formed on both sides. When a vortex is formed on one side, then a similar vortex is formed on the other side and this causes the first one to be shed [1]. For detailed discussions on the theoretical background of this phenomenon *Section 3.0.0 of Chapter V* may be referenced. One flow-measuring instrument that has been developed based on this is discussed in Chapter V.
- *Swirl:* Fluid rotation about the circular pipe axis. Swirl is the tangential flow component of the velocity vector. There are swirl type flow meters used for flow measurement. This is little different from a vortex flow meter and is discussed in Chapter V.

7. **Surface tension:** For the development of surface tension in a liquid there is a need for two kinds of forces as defined below [7].
   - *Cohesive force:* This is the force of attraction between the molecules of a liquid by virtue of which they are bound to each other to remain as one assemblage of particles. It helps to resist tensile stress.

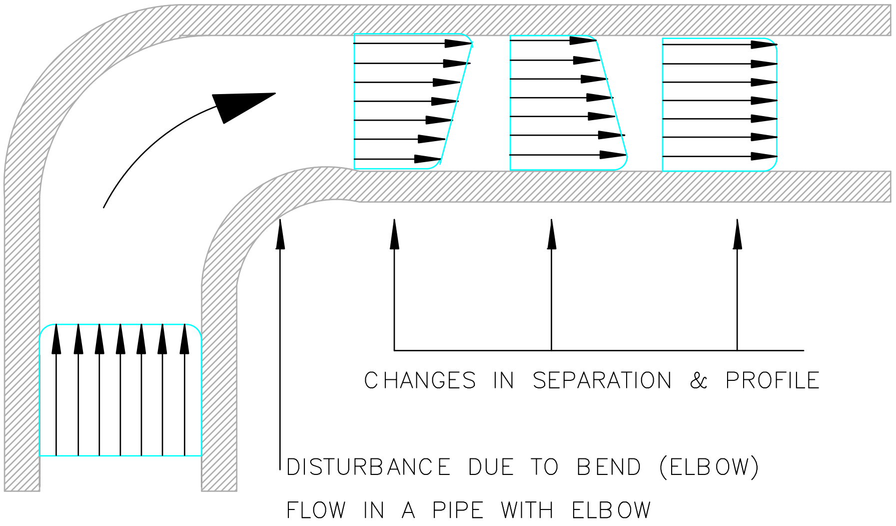


FIGURE I/1.2.2-6 Flow separation and profile after a disturbance.

- *Adhesion force:* This is the force of attraction between unlike molecules, i.e., between the molecules of different liquids or between the molecules of a liquid and those of a solid body when they are in contact with each other. ***Adhesion*** enables it to adhere to another body.

  Therefore, liquid molecules exhibit cohesive forces that bind them to each other. The molecules below the surface are generally free to move within the liquid and they move at random and are subject to equal force in each direction. When they reach the surface they reach a dead end, on account of the absence of molecules above the surface to attract or pull them out of the surface. At this point at the surface the net downward force is at its maximum, so they stop and return back into the liquid. Work is done on each molecule arriving at the surface against the action of an inward force. Thus mechanical work is performed in creating a free surface or in increasing the area of the surface [7]. This is at the cost of potential energy. So, at the condition of stable equilibrium a thin layer of a few atomic thicknesses at the surface is formed. However, this is formed by the system with potential energy at its minimum. This cohesive bond exhibits a tensile strength for the surface layer and this is known as surface tension. The magnitude of surface tension is defined as the tensile force acting across an imaginary short and straight elemental line divided by the length of the line [7]. The dimensional formula is F/L or MT^{-2}. It is usually expressed in N/m in SI units. It shows a slight decrease with an increase in temperature. Surface tension causes an interface of two liquids/liquid–solid/liquid–gas, etc. This is included here as it shows some effect in slurry flow measurement, e.g., bubble formation.

8. **Vapor pressure:** All liquids tend to evaporate or vaporize. Molecules constantly escape from a liquid surface and an equal number constantly enter the surface when there is no energy addition. The number of molecules escaping from the surface or reentering will depend upon the temperature. These escaped molecules above the free surface exert a certain pressure. This pressure is known as the vapor pressure corresponding to the temperature. At an elevated temperature, more molecules will leave than reenter the surface to increase the vapor pressure. This means that vapor pressure increases with temperature. In a confined area, vapor pressure goes on increasing until an equilibrium condition evolves, when the rate at which the number of vapor molecules striking back at the liquid surface and condensing is equal to the rate at which they leave from the surface; the space above the liquid then becomes saturated with vapor. The pressure at which it occurs is called the saturation pressure. The temperature corresponding to the pressure is known as the saturation temperature. From the above it can be seen that the vapor pressure of a given liquid is a function of temperature and hence the vapor pressure increases with the increase in temperature. Therefore, the phenomenon of boiling of a liquid is closely related to the vapor pressure. When the vapor pressure of liquid becomes equal to the total pressure impressed, then the liquid starts to boil. Therefore, boiling can be achieved by increasing the temperature or lowering the surrounding pressure to the vapor pressure.

   With the discussions on general terms related to flow measurement concluded we now discuss the basics of fluid mechanics essential for flow measurement.

9. **Coanda effect:** According to Bernoulli's energy balance equation, a slow-moving high-pressure fluid becomes a fast-moving low-pressure fluid at the nozzle exit forming

a jet. The same theory has been utilized in designing the wings of aircraft. However, in 1930, the Romanian engineer Henri Coanda discovered another effect popularly known as the Coanda effect or wall attachment effect, which is more effective in producing lift. *What is Coanda effect?* "*Coanda effect: A moving stream of fluid in contact with a curved surface will tend to follow the curvature of the surface rather than continue traveling in a straight line.*" (Courtesy of http://www.discoverhover.org/infoinstructors/guide8.htm).

When a fluid moves across a surface a portion of the friction, known as the "skin friction" (something similar to the skin effect of the current!) occurs between the fluid and the surface, and tends to slow down the moving fluid. This resistance to the flow, pulls the fluid towards the surface. So, for the Coanda effect a jet flow attaches itself to a nearby surface and remains attached to it even when the surface curves away from the initial jet direction. This effect is utilized in air condition design also. In fluid flow measurement the same principles have been utilized in the fluidic meters that are discussed later.

10. **Snell's law for ultrasonic measurement:** The reader may recall the laws of refraction in geometrical optics; in case of ultrasonic waves the same is applicable. The angle of incident of the ultrasonic wave is extremely important for better measurement accuracy. When a transducer is mounted externally it has to cross three media, e.g., the transducer, pipe, and fluid. In each case there will be refraction. Referring to Fig. I/1.2.2-7, it can

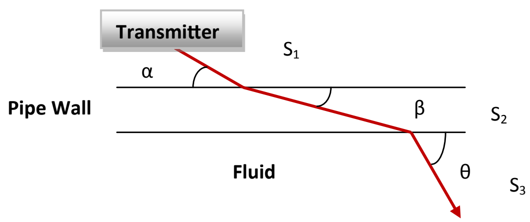


FIGURE I/1.2.2-7 Ultrasonic signal refraction.

be seen that there are three angles involved in two interface points. Naturally, to know exactly where the other transducer to be placed, it is important to know at what angle it reaches the bottom. As per Snell's law for sound "the ratio of the angle of incident to any medium and sound velocity in that medium is constant." In such a case the relationship between the various media can be established by Eq. I/1.2.2-10.

$$\cos\alpha/C_{s1} = \cos\beta/C_{s2} = \cos\theta/C_{s3} = \text{constant} \tag{I/1.2.2-10}$$

This will be required for ultrasonic flow meter discussions.

11. **Law of electromagnetic induction:** From Faraday's second law of electromagnetic induction one gets that the magnitude of induced emf (electromotive force) is equal to the rate of change of flux linkages with the coil. Faraday's law also tells us that inducing a voltage into a conductor can be done by either passing it through a magnetic field, or by moving the magnetic field past the conductor. Faraday's law of electromagnetic induction has been utilized in electromagnetic flow meters, where the process fluid acts as a conductor and electrodes are used to measure the induced emf.
12. **Coriolis' effect:** Coriolis' effect represents an inertial force. According to this effect, if the ordinary Newtonian laws of motion of bodies are to be used in a rotating frame of reference, an inertial force would act on the body and this needs to be taken into consideration for developing an equation of motion. This force will act on the right or left direction of body motion for counterclockwise or clockwise rotation of the reference frame, respectively. Therefore, the effect of the Coriolis force is an apparent deflection of the path of an object that moves within a rotating coordinate system. The object does not *actually* deviate, but it appears to

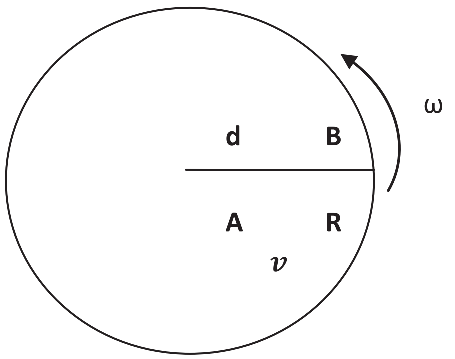


FIGURE I/1.2.2-8 Coriolis' effect.

be a deflection on account of the motion of the coordinate system. Coriolis' effect is the inertial force necessary to be applied to move a mass from A to B when they are in a rotational frame as shown in Fig. I/1.2.2-8. See Section 3.1.4 for further details.

2.0.0 BASIC FLUID MECHANICS

Accurate measurement of a flowing medium is always is very important in plants and industrial applications. The basic approach of the given measurement technique depends on the type of flowing medium, e.g., liquid/gas, the nature of the flow, i.e., laminar/turbulent, etc. [17]. As discussed earlier, there are a few influencing parameters like velocity, pressure, temperature, density, viscosity, turbulent intensity, etc. It is therefore *recommended* that this part of the discussions shall be read in *conjunction* with the relevant parts of the previous Section 1.0.0. One of the major application areas of fluid mechanics is determination of flow in a flow conduit especially for head type meters. This is of prime importance for flow measurement and control. In this section this will be discussed at length. While discussing these, associated requirements from influencing factors will also be discussed in the light of fluid mechanics. The discussion begins with Bernoulli's equation.

1. **Conservation of energy:** From elementary physics it is known that when a ball is dropped from a height, initially it has potential energy (PE) and finally when it touches the ground it has kinetic energy (KE). While traveling, at various points potential energy is transformed into kinetic energy and the height is reduced. So, if a ball with mass "m" starts with zero initial velocity from height "h" and attains velocity v at the time it strikes the ground, then, initial KE = 0, PE = mgh, final PE = 0 KE½mv^2 and at intermediate points it had both PE and KE. From conservation of energy, the initial PE = final KE; mgh = ½mv^2, hence

$$v^2 = 2gh \text{ or } v = (2gh)^{1/2} \qquad \text{(I/2.0.0-1)}$$

2. **Hydrostatic application:** Another important issue is hydrostatic pressure (mainly of liquid) due to the level (datum) difference. This will also be necessary for flow determination with the help of Bernoulli's theorem. A pipe is filled with medium with density (ρ), and is located in an inclined manner so that there is a height difference of points in the pipe as shown in Fig. I/2.0.0-1A, i.e., a point with pressure P_1 is located at Z_1 height above the datum level and a point with pressure P_2 is located at Z_2 height above the datum level, then $P_1 - P_2 = (Z_2 - Z_1)\cdot$ density(ρ)·g, i.e., from the basics of hydrostatics it will be

$$P_1 - P_2 = (Z_2 - Z_1)\rho g$$

or,

$$P_1/\rho + Z_1 g = P_2/\rho + Z_2 g \qquad \text{(I/2.0.0-2)}$$

3. **Derivation of the energy equation:** Referring to Fig. I/2.0.0-1B, an attempt is made to derive the energy equation. Let there be one conduit with cross-section A, with flowing fluid with pressure P. Now, if a mass of "m" of flowing fluid is moved from point "a" to point "b" with velocity "v," at point "a," situated at distance Z above the datum level, potential energy (PE) = mgZ. Hence, for unit weight, PE will be:

$$mgZ/mg = \mathbf{Z}. \qquad \text{(I/2.0.0-3)}$$

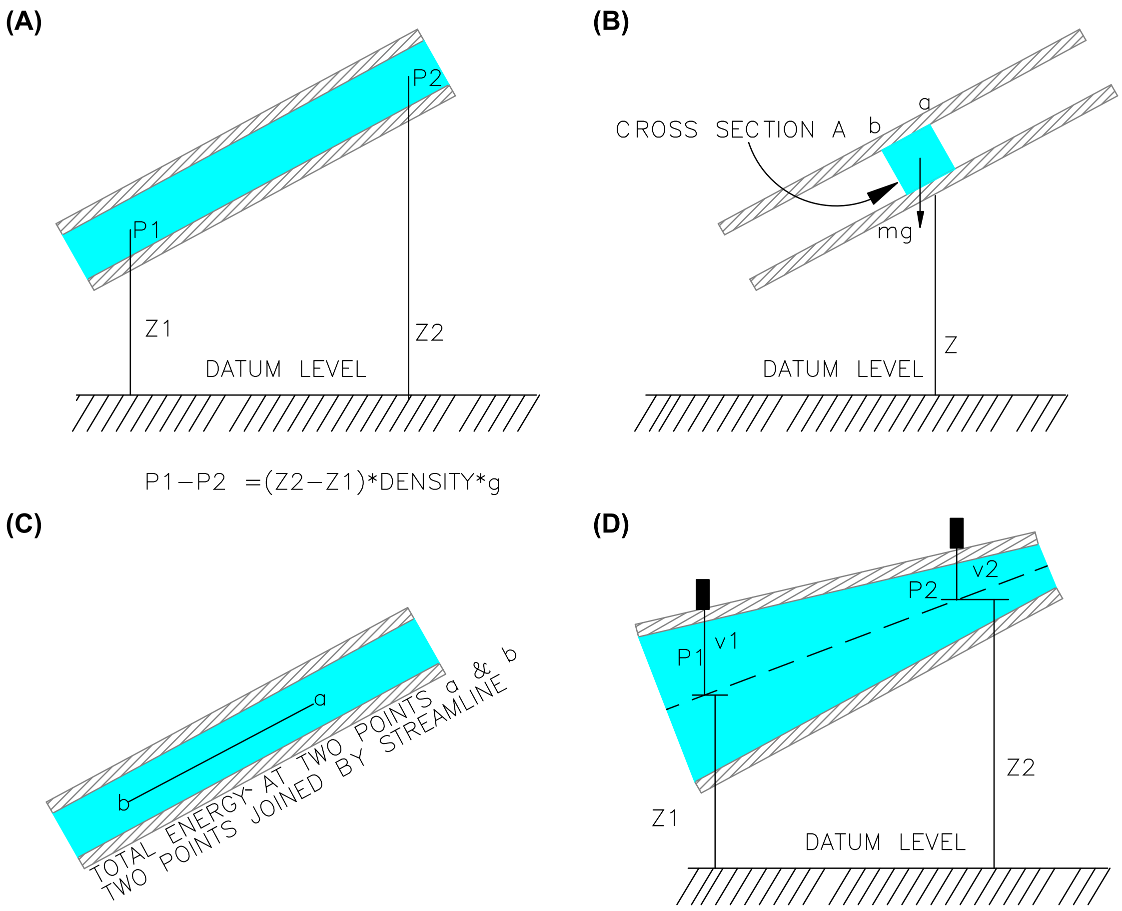


FIGURE I/2.0.0-1 Bernoulli's equation application. (A) Pressure due to level difference. (B) Derivation of Bernoulli's equation. (C) Application of Bernoulli's theorem. (D) Application of Bernoulli's equation for flow calculation.

Similarly kinetic energy for mass will be equal to

$$1/2mv^2. \quad \text{(I/2.0.0-4)}$$

So, kinetic energy for unit weight will be equal to

$$\mathbf{1/2(v^2/g)} \quad \text{(I/2.0.0-5)}$$

On account of pressure P it will generate a force "PA" across the fluid block under consideration. When that fluid block of mass "m" crosses area A from a to b and if ρ is the density of the fluid, then the volume crossing will be

$$m/\rho \quad \text{(I/2.0.0-6)}$$

From the figure the distance traversed will be

$$m/(\rho A) \quad \text{(I/2.0.0-7)}$$

Therefore, work done $= P\cdot A\cdot m/(\rho A) = Pm/\rho$;

$$\text{For unit weight work done } = \mathbf{P/(\rho g)} \quad \text{(I/2.0.0-8)}$$

By summing all energies, pressure energy + PE + KE, one gets

$$P/(\rho g) + Z + 1/2(v^2/g) = \text{Constant} \quad \text{(I/2.0.0-9)}$$

Eq. (I/2.0.0-9) is the basis of Bernoulli's equation.

Also, here as all the parameters in Eq. (I/2.0.0-9) have unit length, they are often called heads, e.g., *pressure head* = **P/(ρg)**; *potential head* = Z and *velocity head* = **½(v²/g)**. Fig. I/2.0.0-1C shows the movement from point a to b in a stream line which is defined as a line tangential to the instantaneous velocity vector direction.

4. **Application of energy equation:** To arrive at Bernoulli's theorem let the above conditions be applied in moving from point a to b in a streamline as shown in Fig. I/2.0.0-1. So total energy per ***unit weight*** at "a" will be:

$$P_a/(\rho g) + Z_a + 1/2\left(v_a^2/g\right) = P_b/(\rho g) + Z_b + 1/2\left(v_b^2/g\right) \quad \text{(I/2.0.0-10)}$$

In the above discussions, loss to friction and/or any other forms has not been considered, similarly energy gain from the pump is not considered as that is the basis for Bernoulli's equation. Another interesting fact here is that in a similar manner pipe flow can be calculated. A typical application of Bernoulli's equation for pipe flow calculation has been depicted in Fig. I/2.0.0-1D. Detailed discussion of this has been presented in the following section.

5. **Bernoulli's principles and equation:** With Bernoulli's equation, it is possible to establish an approximate relation between pressure, velocity, and elevation. It is primarily valid in regions of steady, incompressible flow where net frictional forces are negligible. The major approximation in Bernoulli's equation is that *viscosity effects* are negligibly small compared to *other effects.* Naturally this cannot be applied to the entire flow field of interest. However, such an approximation *is* reasonable in certain *regions* of many practical flows. Such regions are referred to as an *inviscid* region for flow. In fluid dynamics, according to Bernoulli's principle; *for an inviscid flow of a nonconducting fluid, an increase in the speed of the fluid occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy.* In a generalized way, it can be stated that, *when an incompressible fluid is flowing, the total of pressure energy, kinetic energy, and potential energy per unit mass should be constant.*

Bernoulli's equation can be considered to be a statement of the conservation of energy principle applied to flowing fluids. Bernoulli's equation is essentially a general and mathematical form of Bernoulli's principle that also takes into account changes in gravitational potential energy. So, Bernoulli's equation relates the pressure, speed, and height of any two points ("a" and "b") in a steady streamline flowing fluid of unit volume with density ρ. So, Bernoulli's equation can be written as:

$$P + 1/2\rho v^2 + Z\rho g = \text{constant.} \quad \text{(I/2.0.0-11)}$$

where P = static pressure, ρ = density of fluid; Z = elevation from datum. When P is **static pressure**, the term "½ρv²" is known as ***dynamic pressure***. By considering z = 0, i.e., at datum level one can argue that in a closed pipe the sum of static pressure and dynamic pressure is constant.

With reference to Fig. I/2.0.0-1D, it can be written as:

$$P_1 + 1/2\rho v_1^2 + Z_1\rho g = P_2 + 1/2\rho v_2^2 + Z_2\rho g \quad \text{(I/2.0.0-12)}$$

where the expression on the left-hand side (LHS) with suffix 1 represents the parameter at the upstream of the constriction (or restriction, e.g., as an orifice), and the same on the right-hand side (RHS) with suffix 2 representing the parameter at or after the constriction (or restriction, e.g. as an orifice) in a pipeline.

6. **Applicability of Bernoulli's equation:** Bernoulli's equation is quite powerful and with the help of this equation it is possible to calculate pipe flow, etc. However, the equation has some limitations on account of certain assumptions made at that point in time.

Major limitations of Bernoulli's equation mainly encompass the following.

- Flow considered is a steady irrotational flow.
- It speaks of flow from one point to another in a streamline but not between two streamlines.
- Density is constant or a function of pressure, indicating incompressible fluid. However, it is possible to apply it to compressible fluid also (with certain modifications).
- External force must be conservative, i.e., derivable from potential energy [18].
- Velocity is derivable from velocity potential [18] and by using Bernoulli's equation, only the mean velocity (of the liquid) should be taken into account because the velocity of liquid particles is not uniform.
- In Bernoulli's equation all other external forces are neglected, which is not possible in practical applications.
- Any energy extracted from flow or supplied to the flow has to be taken into account.
- In turbulent flow some kinetic energy is converted into heat energy and in a viscous flow some energy is lost due to shear forces.
- If the liquid is flowing through a curved path, the energy due to centrifugal forces should also be taken into account.

  We now discuss how Bernoulli's equation are applied for flow measurement, which of prime importance to us.

2.1.0 Bernoulli's Equation for Pipe Flow Measurement

In this section efforts will be made to derive a pipe flow equation by applying Bernoulli's equation. The discussions start with the continuity equation.

2.1.1 CONTINUITY EQUATION

When fluid is in motion, it must move in such a way that conservation of mass law is followed, i.e., the mass of fluid in a flow tube is constant. This means that mass flowing in = mass flowing out.

This is the continuity equation. Mathematically it can be represented by:

$$m_1 = m_2$$

where m_1 and m_2 represent inflow and outflow of mass.

So,

$$\rho V_1 = \rho V_2$$

where ρ is fluid density and V_1 and V_2 are volume of inflow and outflow of fluid.

Or,

$$\rho A_1 v_1 \Delta t = \rho A_2 v_2 \Delta t$$

where A_1 and A_2 are upstream and downstream area and v_1 and v_2 are velocity at upstream and downstream of restriction and Δt is a small time difference. Then

$$A_1 v_1 = A_2 v_2 = q = V/t = \text{constant E} \qquad \text{(I/2.1.1-1)}$$

Eq. (I/2.1.1-1) represents the continuity equation.

2.1.2 BERNOULLI'S EQUATION FOR FLOW CALCULATIONS

The discussions start with the help of Fig. I/2.0.0-1D. In this figure it is clear that there are two sections. One is wider, where the pressure is P_1 and velocity v_1. The other part is slightly constricted, where pressure and velocity are represented by P_2 and v_2, respectively. In this section flow goes from the wide section to the constricted section. Instead of considering wider and constricted sections, the same section with a restriction, such as an orifice, could also be used to derive the calculation. As per Bernoulli's equation or principles it is known that, in a closed pipe, the density will not change. Now if unit weight of fluid enters the pipe then by the equation of continuity discussed in Section 2.1.1 above, unity weight must also leave the closed pipe. If the flowing

fluid has internal energy in the wider and constricted sections, these are designated I_1 and I_2. Then, by applying Eq. (I/2.0.0-12), one can write

$$P_1 + 1/2\rho v_1^2 + Z_1\rho g + I_1 = P_2 + 1/2\rho v_2^2 + Z_2\rho g + I_2 \quad \text{(I/2.1.2-1)}$$

Here one thing to be noted is that as per Bernoulli's principle, density remains constant (see Subsection 2.0.0.6), so in both sides the same density ρ is considered. Also, as long as temperature in both sections remains constant, then $I_1 = I_2$ [19], so, one gets

$$P_1 + 1/2\rho v_1^2 + Z_1\rho g = P_2 + 1/2\rho v_2^2 + Z_2\rho g \quad \text{(I/2.1.2-2)}$$

This is basically the same as Eq. (I/2.0.0-12). Now, dividing both sides by ρg, Z is freed.

$$(P_1/\rho g) + \left(v_1^2/2g\right) + Z_1 = (P_2/\rho g) + \left(v_2^2/2g\right) + Z_2 \quad \text{(I/2.1.2-3)}$$

Considering the horizontal level as the datum level, a manometer is placed at the two tappings to measure pressure, then fluid height at the upstream tapping with respect to the datum will be $(P_1/\rho g) + Z_1$ and at the downstream tapping it will be $(P_2/\rho g) + Z_2$.

So, if "h" is the difference in the manometer between the two tappings then

$$h = (P_1/\rho g) + Z_1 - (P_2/\rho g) - Z_2 \quad \text{(I/2.1.2-4)}$$

Combining Eqs. (I/2.1.2-3 and I/2.1.2-4) one gets

$$v_2^2 - v_1^2 = 2gh; \quad \text{(I/2.1.2-5)}$$

and again from Eq. (I/2.1.1-1) one gets $v_1^2 = (A_2/A_1)^2 v_2^2$ and so, putting the value of v_1 in Eq. (I/2.1.2-5) one gets that

$$v_2^2\left(1 - A_2^2/A_1^2\right) = 2ghm^2$$

or,

$$v_2 = (2gh)^{1/2}/\left(1 - A_2^2/A_1^2\right)^{1/2}$$

or,

$$v_2 = \sqrt{2gh}\Big/\sqrt{(1 - m^2)} \quad \text{(I/2.1.2-6)}$$

where the area ratio is represented by **"m."** Also $1/(1 - m^2)^{1/2}$ is referred to as ***velocity approach*** and represented by E. So

$$v_2 = E\cdot\sqrt{2gh} \quad \text{(I/2.1.2-7)}$$

Therefore, volume flow

$$q = A_2\cdot v_2 = A_2\cdot E\sqrt{2gh} \quad \text{(I/2.1.2-8)}$$

Now putting the value of $dp/\rho = hg$ and simplifying $2dp\rho$

$$q = A_2\cdot E\sqrt{2dp/\rho} \quad \text{(I/2.1.2-9)}$$

$$\text{Mass flow} = q\rho = A_2\cdot E\sqrt{2dp\rho} \quad \text{(I/2.1.2-10)}$$

2.1.3 FLOW EQUATION IN TERMS OF PIPE GEOMETRY

In the previous section discussions were put forward with different elevations for upstream and downstream with constriction for flow measurement. In this case a flow restriction has been considered in a horizontal pipe, meaning $Z_1 = Z_2$.

From Eq. (I/2.1.2-3), e.g., in a horizontal pipe; meaning $Z_1 = Z_2$

$$(P_1/\rho g) + \left(v_1^2/2g\right) = (P_2/\rho g) + \left(v_2^2/2g\right) \quad \text{(I/2.1.3-1)}$$

or

$$P_1 - P_2 = dp = \Delta p = \frac{\rho}{2}\left(v_2^2 - v_1^2\right) \quad \text{(I/2.1.3-2)}$$

Again, from Eq. (I/2.1.1-1), we have $A_1\cdot v_1 = A_2\cdot v_2$ or $v_1 = (A_2/A_1)\cdot v_2$, so for a closed pipe of inside diameter D and restriction bore d one gets $v_1 = (d^2/D^2)\cdot v_2$ or $v_1 = (d/D)^2\cdot v_2$; putting the value of β (d/D) from Fig. I/2.1.2-1 one gets

$$v_1 = (\beta)^2\cdot v_2 \quad \text{(I/2.1.3-3)}$$

Beta Ratio: Velocity approach is the area ratio of two sections. Now in case of a closed pipe if inside diameter of the pipe is "D" and the same for the restriction (say orifice plate) is "d" then the ratio of d/D is referred to as Beta Ratio. So,

β = Bore/Pipe ID = d/D ; It is one of the major geometric parameter in Flow calculation. Beta is always less than 1. *Square edge orifice 0.2- 0.75 (0.7 max design), Quadrant orifice 0.24- 0.6, Venture 0.4-0.7 [source:20].*

FIGURE I/2.1.2-1 Beta ratio for flow elements. *Adapted from Process Design Practices Flow Meters and Orifices; CK, December 2009, http://www.korf.co.uk/PDP%2006-FO-P5_P14.pdf.*

By combining Eq. (I/2.1.3-2 and I/2.1.3-3) one gets

$$\sqrt{2\Delta p/\rho(1-\beta4)} = v_2 \qquad \text{(I/2.1.3-4)}$$

$$q = A_2 v_2 = \pi\left(d^2/4\right)\sqrt{2\Delta p/\rho(1-\beta4)} \qquad \text{(I/2.1.3-5)}$$

$$\text{Mass flow } \mathbf{q_m = \pi\left(d^2/4\right)\sqrt{2\Delta p\rho/(1-\beta4)}} \qquad \text{(I/2.1.3-6)}$$

The flow calculations shown in Sections 2.1.2 and 2.1.3 are *theoretical* values because of various assumptions in Bernoulli's equations discussed in Subsection 2.0.0.6 for streamline flow without losses. So, these calculations are far from real values, where the flow is turbulent in most cases, also viscosity effects cannot be ignored in this way. In view of the same some corrections are necessary, as discussed in the following sections. Another interesting issue is that after the restriction there will be some pressure recovery but it cannot recover full-pressure P_1 but at a less value P_3. $P_1 - P_3$ is the *permanent pressure* loss in the system.

2.1.4 DISCHARGE COEFFICIENT

Discharge coefficient (C_d) (as per standard ISO 5167:2003 it is designated as "C," however since C_d is more popular, it is used in the book) is defined as the ratio of actual flow by theoretical flow, so,

$$\text{Discharge coefficient } C_d = (\text{Actual flow})/(\text{Theoretical flow})$$

i.e., actual flow = $C_d \cdot$theoretical flow (Eq. I/2.1.3-6) or

$$q_m = C_d \cdot \pi\left(d^2/4\right)\sqrt{2\Delta p\rho/(1-\beta4)} \qquad \text{(I/2.1.4-1)}$$

in the case of compressible fluid another factor expansibility factor ε (discussed later), to be multiplied. So, mass flow

$$q_m = C_d \cdot \varepsilon \cdot \pi\left(d^2/4\right)\sqrt{2\Delta p\rho/(1-\beta4)} \qquad \text{(I/2.1.4-1A)}$$

In this case, temperature and density, etc. in both sections are the same, and above flows may be considered as volume flow. From Section 3.3.5 of ISO 5167-1:2003, one gets the following definition.

Discharge coefficient, "defined for an incompressible fluid flow, which relates the actual flow rate to the theoretical flow rate through a device, and is given by the formula for incompressible fluids." Using this, C_d ("C" in the standard) is defined as

$$C(=C_d) = \left\{Qm \cdot \sqrt{(1-\beta4)}\right\} \Big/ \times \left\{\pi\left(d^2/4\right)\sqrt{2\Delta p\rho}\right\}. \qquad \text{(I/2.1.4-1B)}$$

In Section 2.1.2 and Eq. (I/2.1.2-6) the velocity approach has already been defined. After having a close look at this for a closed circular pipe it can be argued that the term $\mathbf{1/\sqrt{(1-\beta4)}}$ ***is the velocity approach***.

TABLE I/2.1.5-1 Relation of Discharge Coefficient and Diameter Ratio [21]

Device	Beta (Min.)	Beta (Max.)	C_d
Thin sharp edge orifice			0.61
Machined Venturi nozzle	0.4	0.75	0.995
Rough weld Venturi nozzle	0.4	0.7	0.985
Rough cast Venturi nozzle	0.3	0.77	0.984

2.1.5 FLOW COEFFICIENT

There is another important term, flow coefficient, which is defined as follows:

$$\textbf{Flow coefficient} = \mathbf{C \cdot 1 \Big/ \sqrt{(1-\beta 4)}} \text{ or } \mathbf{C_d \cdot 1 \Big/ \sqrt{(1-\beta 4)}}$$

C_d is a function of the jet size or *area ratio* $= A_{vc}/A_2$ where A_{vc} = *area in "vena contracta"* discussed below. For a primary device, C_d is the dimensionless parameter determined using an incompressible fluid. C_d is dependent on Reynolds number (Re) for a given geometry. It relates the resistance coefficient discussed later in Subsection 2.1.6.2. C_d often is considered as calibration constant for a primary device. The typical relationship of C_d with various beta values has been elaborated in Table I/2.1.5-1. R_e varies with pressure, temperature, viscosity and flow, as does C_d.

2.1.6 RELATED DISCUSSION TERMS

1. **Vena contracta:** The vena contracta was probably first conceived by Torricelli in 1643. It is the reduction in the area of a fluid jet after it emerges from a circular aperture. The vena contracta is the minimum jet area that appears just downstream of the restriction. The velocity of the fluid will be at its highest and the pressure at the lowest in the "vena contracta."
2. **Resistance coefficient (K):** The resistance coefficient represents the multiple of velocity heads that will be lost by fluid passing through the fitting. The resistance coefficient (K) allows the user to characterize the pressure loss through fittings in a pipe. It is related to C_d by

$$K = 1/C_d^2. \quad \text{(I/2.1.6-1)}$$

3. **Isentropic exponent:** According to ISO 5167-1:2003, the isentropic exponent is defined as the ratio of the relative *variation* in pressure to the corresponding relative *variation* in density under elementary reversible adiabatic (isentropic) transformation conditions. Factor k is a property of the media and varies with the pressure and temperature of the medium also. The isentropic exponent "κ" appears in different formulae for the expansibility (expansion) factor ε discussed below. It varies with the nature of the gas and with its temperature and pressure conditions. There are many gases and vapors for which no values for k have been published so far (ISO 5167-1:2003). In such cases, as per standard, "the ratio of the specific heat capacity at constant pressure to the specific heat capacity at constant volume of ideal gases can be used in place of the isentropic exponent," i.e., C_p/C_v—specific heat ratio. For air and diatomic molecule gases it is 1.4.
4. **Pipe Reynolds number (Re_D) and orifice Reynolds number (Re_d):** Dimensionless Reynolds number has been defined in Subsection 1.2.2.3. Since the velocity at the two sections of flow-measuring systems are not the same naturally there will be two different Reynolds numbers for the two sections of flow-measuring systems—typically as shown in Fig. I/2.0.0-1D (or Fig. I/2.1.3-1) as velocity of two sections are different. So,

$$\text{Pipe Reynolds number}(Re_D) = v_1 D/\nu_1 = (4Q_m)/(\pi \mu_1 D) \quad \text{(I/2.1.6-2)}$$

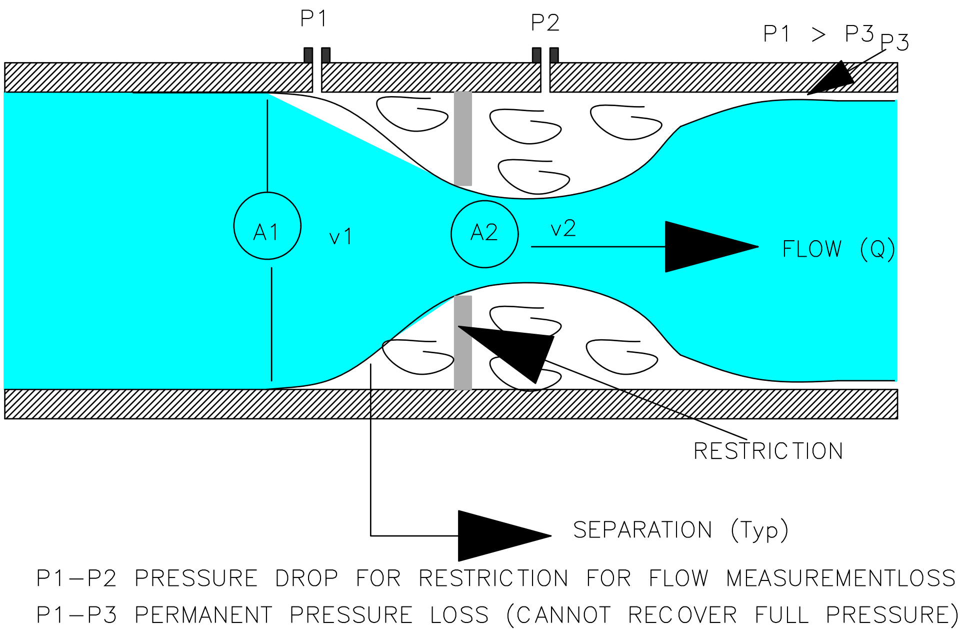


FIGURE I/2.1.3-1 Calculation of flow through restriction (horizontal).

$$\text{Orifice Reynolds number}(Re_d) = Re_D/\beta \tag{I/2.1.6-3}$$

Eqs. (I/2.1.6-2 and I/2.1.6-3) may be compared with the expressions given in Subsections 3.3.2.1 and 3.3.2.2 of ISO 5167-1:2003.

5. **John Thomson coefficient:** This deals with the temperature pressure coefficient, μ_{JT}, i.e., rate of change of temperature with respect to (WRT) pressure at constant enthalpy. So,

$$\mu_{JT} = \frac{\partial T}{\partial P} \text{ at H (enthalpy) constant.} \tag{I/2.1.6-4}$$

2.1.7 EXPANSIBILITY FACTOR

In Eq. (I/2.1.4-1), the coefficient discharge has been defined for an incompressible fluid. For compressible fluids another factor expansibility factor is necessary to take care of the compressibility. Different fluids, i.e., gases and steam, have different compressibility. This is because each has a different molecular form. So, based on their form, fluid molecules are more or less compressed when they pass through any restriction (orifice) [22]. Factor ε depends on the pressure relation and the isentropic exponent κ (defined in Subsection 2.1.6.3). As per ISO 5167-1:2003, coefficient ε is used to take into account the compressibility of the fluid. As per ISO 5167-1:2003 and Eq. (I/2.1.4-1A), ε is given by

$$\varepsilon = \left\{q_m \cdot \sqrt{(1-\beta 4)}\right\} \Big/ \left\{\left(\pi d^2/4\right) \cdot C_d \sqrt{2\Delta p \rho 1}\right\} \tag{I/2.1.7-1}$$

From Eq. (I/2.1.7-1) it is clear that the ratio given above (except C_d) is dependent on the Reynolds number, pressure ratio, and isentropic exponent of gas (see Subsection 2.1.6.3). In the case of *incompressible* fluid $\boldsymbol{\varepsilon = 1}$ but for compressible fluids $\varepsilon < 1$.

2.1.8 MEASUREMENT AND FLOW COMPUTATION

Standard ISO 5167-1:3 provide specific guidelines for this. In order to measure and compute flow one needs to install a primary flow device in the line and to measure the pressure difference between the upstream pressure at a suitable location depends on the tapping style discussed in

Chapter II and a pressure at a suitable location (depends on tapping style discussed in Chapter II) at the downstream of the restriction. Various tapping styles and primary elements depend on many factors, such as pipe size, flow quantity, static pressure, etc. The mass flow rate can be determined from Eq. (I/2.1.3-6) (within the uncertainty limits in ISO 5167) as follows:

$$q_m = C_d \cdot \varepsilon \cdot \pi \left(d^2/4\right) \sqrt{2\Delta p \rho/(1-\beta 4)} \quad \text{(I/2.1.8-1)}$$

$$\text{Volume flow } q_v = q_m/\rho \cdot = C_d \cdot \varepsilon \cdot \pi \left(d^2/4\right) \sqrt{2\Delta p/\rho(1-\beta 4)} \quad \text{(I/2.1.8-2)}$$

For gas flow one needs to note that when gas passes through the restriction, the change of pressure is so abrupt that it can hardly absorb any heat from the surroundings. When it passes through the restriction it expands on account of pressure reduction and so it does some work. As it is unable to receive any external energy it has to spend its heat energy, meaning the temperature falls. Hence temperature is not constant, and Boyle's law is not applicable. It undergoes adiabatic expansion. From elementary physics it is known that for adiabatic expansion $(PV)^{\Upsilon} =$ constant; where $\Upsilon = C_p/C_v$ (see Eq. I/1.1.2-5). The value of Υ varies, e.g., dry air: 1.4; other diatomic gas: 1.66; monatomic gas: 1.33. Short discussions are now put forward for sizing primary elements in line with ISO 5167-1:2003 (practical approach). Unless otherwise stated, the standard referred to here is ISO 5167.

1. **Determination of d/D ratio and flow computation:** Standard ISO 5167-1: 2003 provides guidance for determination of beta. When determining the beta ratio in almost all cases the C_d and ε values are not known. For this meters based on *flow rate* and corresponding selected ΔP *range* for a specific pipe are first selected. From Eq. (I/2.1.8-1) unknown quantities are segregated and put in the left side, while know parameters such as *flow rate range, ΔP range*, etc. are on the RHS. Also, d is replaced by βD, where for a given pipe D is known. So, by rearranging Eq. (I/2.1.8-1) one gets:

$$\left(C_d \cdot \varepsilon \cdot \beta^2\right) \Big/ \sqrt{(1-\beta 4)} = \left(4Q_m\right) \Big/ \left(\pi D^2\right) \left(\sqrt{2\Delta p \rho}\right) \quad \text{(I/2.1.8-3)}$$

Now the iterative method discussed in Annex I of ISO 5167-1:2003 may be applied to determine beta. Once this is done it is a question of arithmetic computation using the numerical values.

The determination of major parameters like density, static pressure, and temperature is important for accurate flow measurement. As per standard any method of determining reliable values of these parameters is acceptable as long as it does not interfere with the distribution of the flow in any way at the cross-section where the measurement is made.

2. **Density:** It is necessary to know the density of the fluid which can either be measured directly or be calculated from an appropriate equation, with knowledge of the absolute static pressure, absolute temperature, and the composition of the fluid at that location.
3. **Static pressure:** The static pressure of the fluid shall be measured by means of pipe-wall pressure tapping(s) discussed at length later. Tapping for static pressure measurement shall be separate for the same pertinent to ΔP measurement and this shall be located upstream of the restriction [22].
4. **Temperature:** The temperature of the fluid shall preferably be measured downstream of the primary device and shall be located at least equal to 5D (and at most 15D when the fluid is a gas) if the pocket is located downstream (in the case of a Venturi tube this distance is measured from the throat pressure tapping plane; see ISO5167-1:2003). The thermometer well or pocket shall take up as little space as possible. Detailed guidelines for this are available in ISO 5167-2, ISO 5167-3, or ISO 5167-4, depending on the primary device

chosen. The temperature drop from the upstream tapping to the downstream temperature location, ΔT, can be evaluated using the Joule Thomson coefficient, μ_{JT}, which is described in Eq. (I/2.1.6-4).

5. **Standard treatises:** After the above steps, the following standard treatises [22] are applied. These are stated here so that the reader can have a feel for the standard procedure to be followed. However, they are discussed at length subsequently.
   - Allowed variations for different measures (pipe diameter, restriction diameter, up- and downstream straight length requirements, etc).
   - Allowable tolerance of all measures.
   - Structural details of primary elements, including thickness, various angle tolerances allowed, etc.
   - Shaping, placement, and details (hole size, etc.) of various pressure tappings and style.
   - The actual flow rate is calculated from the normal flow rate. As stated earlier, usually the full flow and full meter range is first selected. Usually 0.7 is considered the normal range and hence actual flow is computed by

$$(q_m)_{act} = \sqrt{\frac{\Delta P_{act}}{\Delta P_{nor}}} \cdot (q_m)_{nor} \qquad \text{(I/2.1.8-4)}$$

6. **Interrelation of various parameters:** Various parameters necessary for flow measurements are highly connected with each other. The interrelationship between them has been shown in Fig. I/2.1.8-1, which is based on [22]. This will help the reader to get a good grasp of the issue.

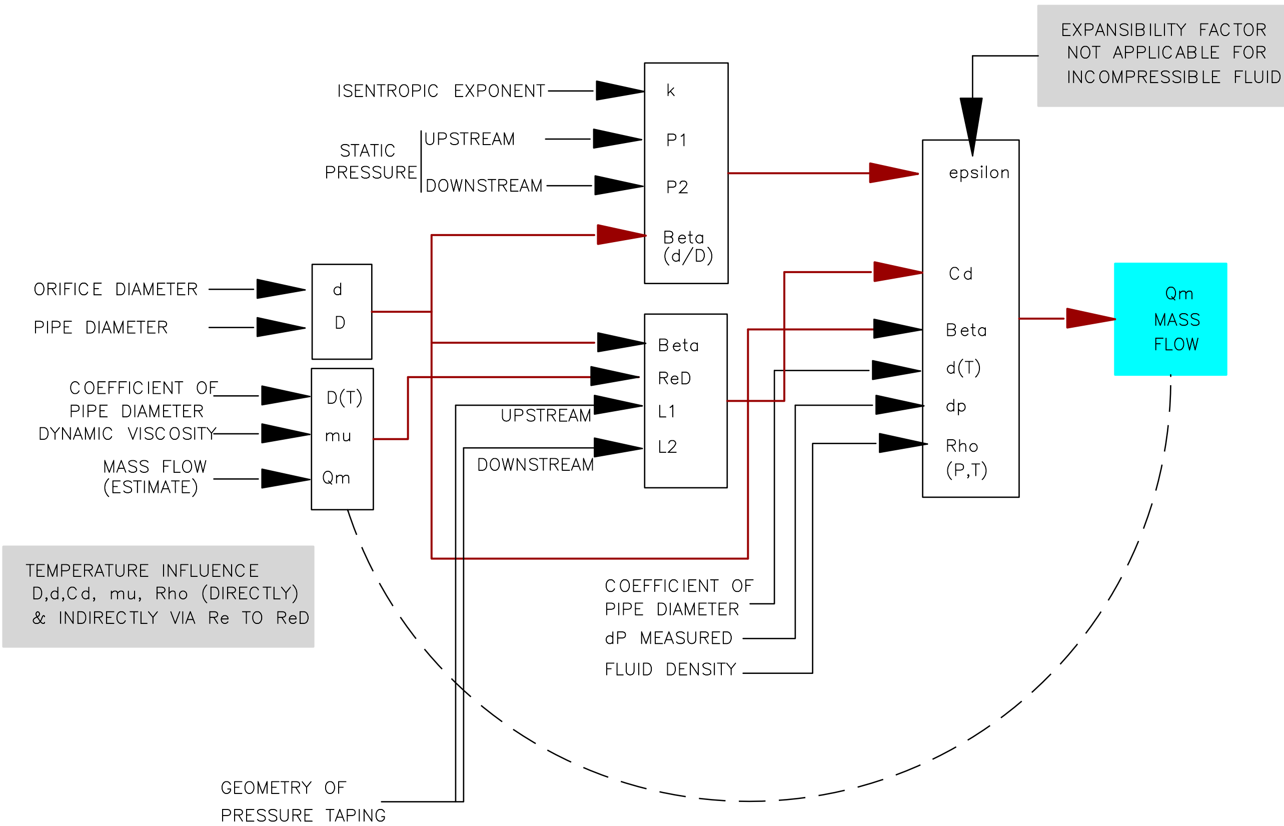


FIGURE I/2.1.8-1 Parameter inter-relations for flow measurement. *Based on an idea from P. Lau, Calculation of Flow Rate from Differential Devices-Orifice Plate, Ematem- Sommerschule; Kloster Seeon; SP Technical Research Institute Sweden, August 2008.*

2.1.9 PRESSURE/TEMPERATURE COMPENSATION FOR FLOW

Head type flow measurements by primary flow elements require a pressure/temperature compensation formula when we use primary flow elements to measure gas/steam flow in pipes with variable operating conditions. The variations in pressure and temperature have a significant effect on gas/steam density, which is why without this pressure and temperature compensation the flow measurement can have large errors [23]. In fact, for variable temperature conditions, density compensation is also necessary for incompressible flow, e.g., temperature compensation feed flow measurements in utility boilers. For head type flow meters pressure and temperature compensations are typically performed upstream and downstream of the flow meter, respectively. Here the flow compensation formula shall be derived for compressible fluid and later it will be used for incompressible fluid (example given above).

It is established from the gas law that

$$PV = nRT$$

where, $P =$ pressure (absolute), $V =$ volume, $n =$ number of moles, $R =$ gas constant, $T =$ temperature (absolute). If Mw is molecular weight then, for mass m; $n = m/Mw$. Again $\rho = m/V$.

So,

$$P \cdot m/\rho = m/Mw \cdot RT \text{ or } p/\rho = RT/Mw \text{ or } \rho = P \cdot Mw/RT$$

Therefore

$$\rho_{real} = P_{real} \cdot Mw/RT_{real} \text{(since R \& Mw is constant)} \quad \text{(I/2.1.9-1)}$$

$$\rho_{design} = P_{design} \cdot Mw/RT_{design} \quad \text{(I/2.1.9-2)}$$

So, by dividing Eq. (I/2.1.9-1) by Eq. (I/2.1.9-2) we obtain

$$\rho_{real} = \rho_{design} \cdot (P_{real}/P_{design}) \cdot (T_{design}/T_{real}) \quad \text{(I/2.1.9-3)}$$

From Eq. (I/2.1.3-5), it is found that Q is proportional to $\sqrt{\Delta p/\rho}$ with other terms being constant for a particular primary element.

Therefore

$$Q = \text{Constant} \cdot \sqrt{\Delta p/\rho}$$

or

$$Q = \text{Constant} \cdot \sqrt{\Delta p/\rho_{design} \cdot (P_{real}/P_{design}) \cdot (T_{design}/T_{real})} \quad \text{(I/2.1.9-4)}$$

Putting the value of ρ_{real} from Eq. (I/2.1.9-3).

Similarly

$$q_m = \text{Constant} \cdot \sqrt{\Delta p \cdot \rho}$$

or

$$q_m = \text{Constant} \cdot \sqrt{\Delta p \cdot \rho_{design} \cdot (P_{real}/P_{design}) \cdot (T_{design}/T_{real})} \quad \text{(I/2.1.9-5)}$$

If one considers design at STP, and temperature $T_c = T_{real}/T_{design} = T_{real}/T_{STP}$ and similarly for pressure $P_c = P_{real}/P_{design} = P_{real}/P_{STP}$ and if $\Delta p = h$ differential head, and ρ_{design} is a known constant and so is put under main heading of Constant, the whole constant is K, then equation Eq. (I/2.1.9-5) changes to

$$q_m = K \cdot \sqrt{h \cdot \frac{P_c}{T_c}} \quad \text{(I/2.1.9-6)}$$

Therefore, the actual measurement is done as shown in Fig. I/2.1.9-1.

Note here that the temperature sensor has been put downstream mainly to avoid an obstruction in the upstream side. Further discussions have been presented in connection with flow computers in Section 5.1.0 of Chapter XI.

Fluid mechanics is a vast subject and it is practically impossible to cover all the details. It is therefore recommended that readers brush up their knowledge on this from a standard book on fluid mechanics and thermodynamics. With these details the discussions on basic fluid mechanics is

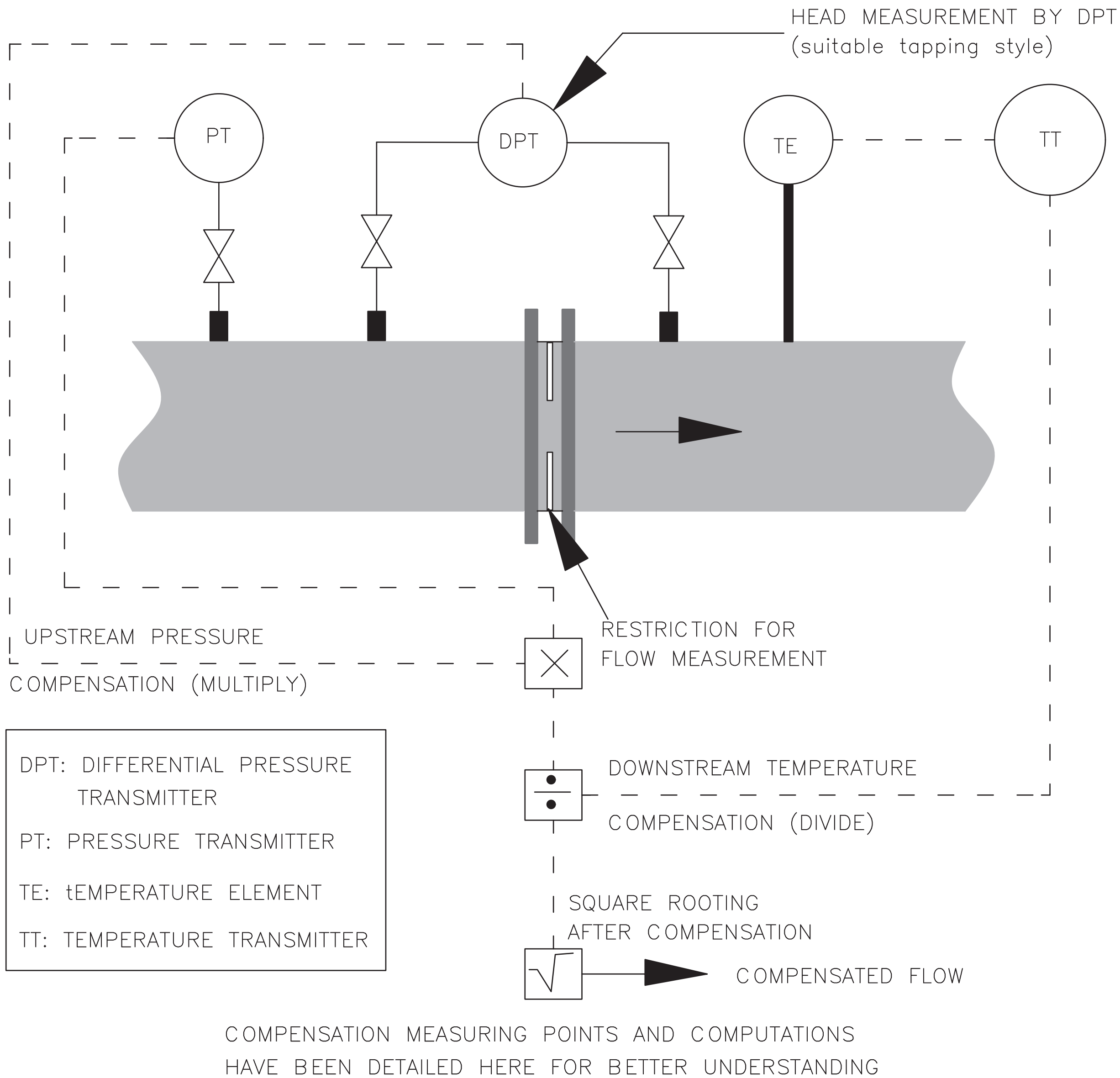


FIGURE I/2.1.9-1 Pressure–temperature compensation for flow.

concluded and we move on to explore various flow-measuring principles to proceed another step for overview of flow metering.

3.0.0 FLOW MEASUREMENT TYPES AND PRINCIPLES

Normally flow measurements refers to fluid flow measurements. In reality this is not the case, there are many other types of flow, such as solid flow (in cement industries, food industries), multiphase flow (in oil exploration and chemical plants), and slurry flow (in mineral processing), which are important for many industrial applications. Although many of the technologies used in fluid flow are also applicable to slurry/multiphase flow measurements they are treated separately. So, flow measurements are first categorized as shown in Fig. I/3.0.0-1.

Based on Fig. I/3.0.0-1, the discussions on various types of flow-measuring systems are

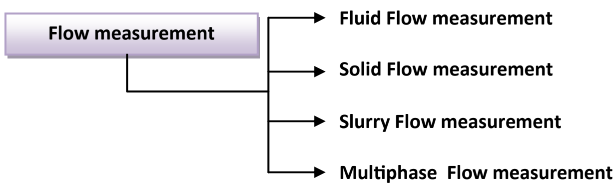


FIGURE I/3.0.0-1 Basic flow measurement categories.

presented. Under fluid flow measurement, flow measurements of both incompressible and compressible fluids are covered. The necessary fluid mechanics have already been covered in the previous section.

3.1.0 Fluid Flow Measurement Types and Principles

In this subsection, the basic principle of operations, and pros and cons of various types of flow meters are discussed. Having gained some knowledge on various general and process-related terms of fluid mechanics, one needs to understand how these are deployed in developing various types of fluid flow meters. These are important in the sense that these ideas will be necessary in selecting a flow meter for the application of interest, i.e., for flow meter selection. Also, based on basic knowledge about the metering principles of each type of meter, details will be developed in subsequent chapters. Therefore, the importance of this part cannot be overestimated. During this discussion most major types of flow-metering devices are covered.

Fluid flow metering in a closed pipe can be classified into four classes: inferential, positive displacement, velocity, and mass. However this is not sacrosanct. When an open-channel flow measurement (frequently encountered in irrigation) is taken into consideration they can be categorized differently, such as differential pressure (head type), positive displacement, velocity, mass, variable area types, and open-channel flow measurement. Some even subcategorize them into mechanical and electrical types. In this connection a typical flow meter categorization has been illustrated in Fig. I/3.1.0-1.

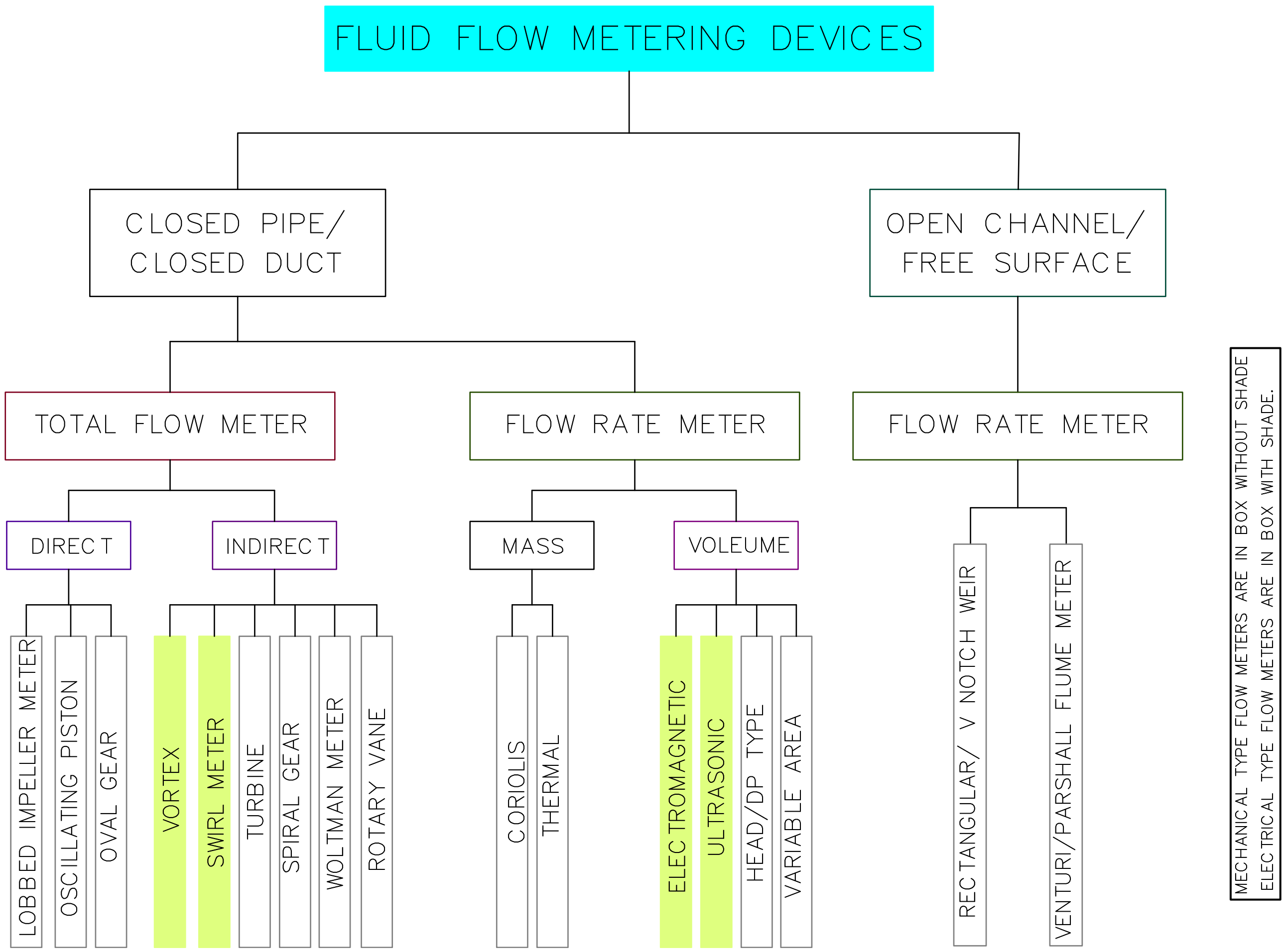


FIGURE I/3.1.0-1 Fluid flow meter types and categorization. *Based on S. Basu, A.K. Debnath, Power Plant Instrumentation and Control Handbook, Elsevier, November 2014, http://store.elsevier.com/Power-Plant-Instrumentation-and-Control-Handbook/Swapan-Basu/isbn-9780128011737/. Courtesy: Elsevier.*

This figure shows that there are a number of ways that these can be categorized. However, there could be other categorization methods, as shown in Fig. I/3.0.1-2. Accordingly, the principle of operation of these is given in a similar order.

3.1.1 INFERENTIAL FLOW METER TYPES AND PRINCIPLES

Inferential flow meters calculate flow rate based on mainly nonflow measurement, with the help of some correlations that have been widely accepted. As discussed above and shown in Fig. I/3.1.0-2, there are two kinds: head type measurement and variable area flow meter. All DP elements are static in nature, i.e., they have no moving parts and most of them can be manufactured with a number of materials (SS 316 is a very popular material). In head type flow measurement, with the help of a restriction, a differential head is created and measured across the restriction. Principles of operations of these types of flow measurements are based on the premise that pressure drop across the meter restriction is proportional to the square of the flow rate. The flow rate is calculated by extracting the square root of the reading (leaving aside other corrections). In the case of an elbow tap meter such differential pressure is created not due to any restriction but due to centrifugal force. In a variable area flow meter, gravitational force of float is balanced by force due to pressure and buoyancy force. At the equilibrium point flow is directly read from the float position (remote transmission is also possible). Let the discussions start with head type meter— orifice plate.

1. **Orifice plate:** Orifices are the most popular fluid flow elements used in process and other industries. The flow characteristics of orifices are very well documented. When an orifice is inserted in a pipeline, it causes an increase in flow velocity and a corresponding decrease in pressure at the downstream. The maximum velocity and minimum pressure are at the vena contracta. An orifice is simply a flat piece of metal with a specific-sized hole (d calculated)

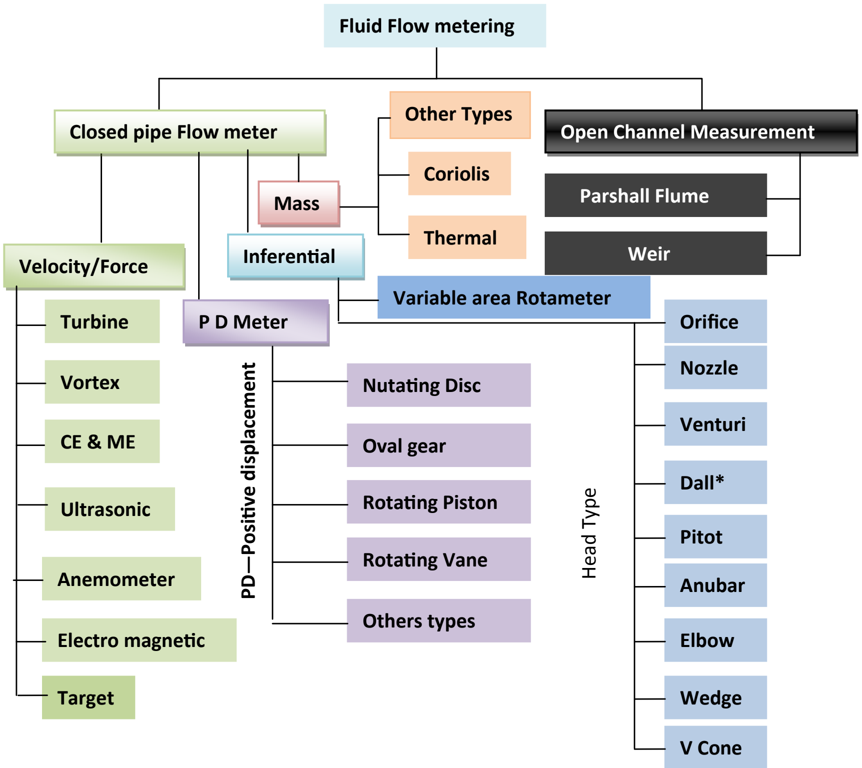


FIGURE I/3.1.0-2 Fluid flow meter divisions. *Dall tube is a category of ASME flow tube. *CE*, Coanda Effect; *ME*, Momentum Exchange.

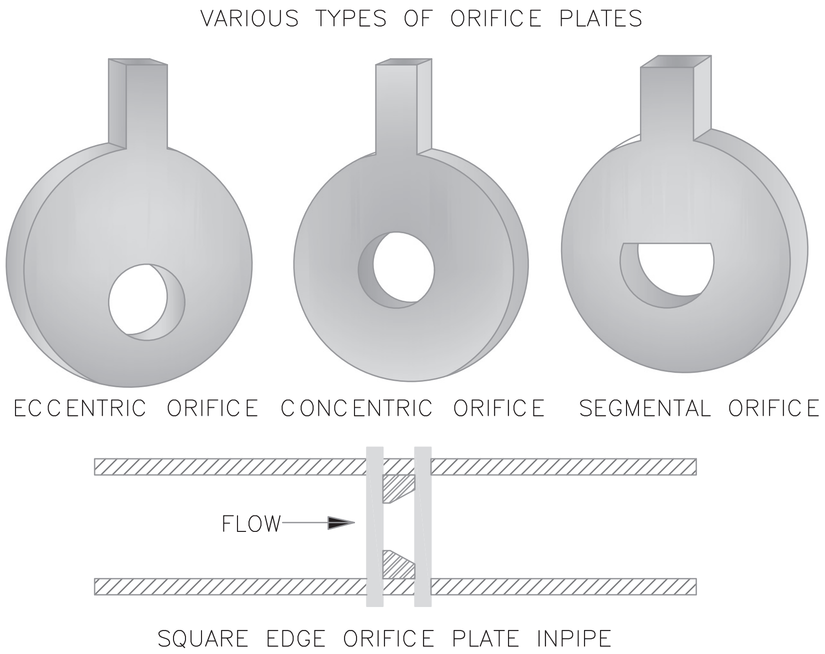


FIGURE I/3.1.1-1 Orifice plate.

bored in the plate. It is less prone to maintenance. It is not only inexpensive but easier to manufacture. Another important issue is that with an increase in the pipe, the cost of the orifice does not increase significantly and no special piping or fittings are necessary. It has a few negative aspects also. It has a rangeability of 5:1 and accuracy is over 2%–4% full scale. It also creates a lot of permanent pressure loss. Mostly orifice plates are of the concentric type. There are other types also such as eccentric and segmental, as shown in Fig. I/3.1.1-1. Detailed discussions are available in Chapter II.

2. **Flow nozzle:** At high velocity a flow nozzle has the capability of handling a higher flow of fluid with the same pressure drop when compared to an orifice plate. This indicates that it has a small beta ratio to provide a higher discharge coefficient. Also, it has better pressure recovery, and hence less permanent loss than an orifice. It has an initial smooth, convergent section, and finally it discharges the flow parallel to the axis of the downstream pipe as shown in Fig. I/3.1.1-2. It has three versions, including the ISA 1932 nozzle commonly used outside the United States [25], the long-radius nozzle, and the Venturi nozzle. It can be used for liquids with suspended solids. In steam flow measurements, especially in utility stations, it finds many applications for high-pressure steam flow.

   It is not suitable for liquids with high viscosity. It is costlier than an orifice and it is available for moderate pipe sizes only. Also, it is difficult to maintain and inspect as the pipe section needs dismantling. The characteristics of a flow nozzle are similar to those of a Venturi.

3. **Venturi:** The discussions start with Fig. I/3.1.1-3, where it is clear to see that it has a gradual tapered restriction at the inlet and outlet (normally a straight portion between the inlet and outlet, and referred to as the throat). It has a very high discharge coefficient and low pressure drop. It helps to eliminate boundary layer separations and hence has less drag. Performance characteristics are well documented [25]. The convergence and throat area is mainly responsible for pressure drop from where any other head type flow device flow is calculated.

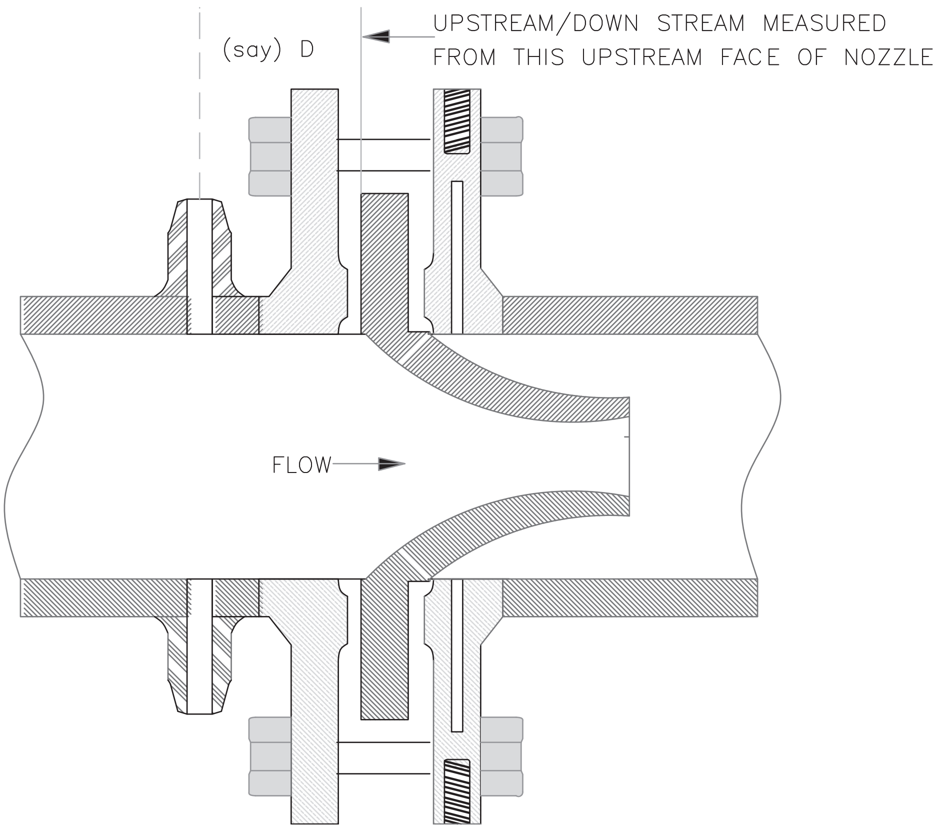


FIGURE I/3.1.1-2 Flow nozzle.

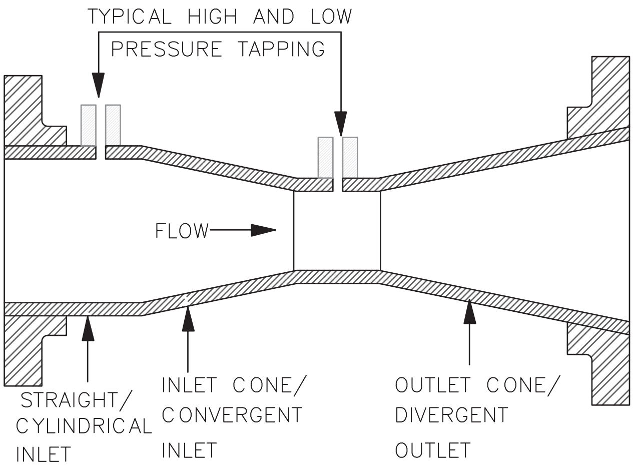


FIGURE I/3.1.1-3 Venturi tube.

There are a few numbers of forms of Venturi available, such as the long-form or classical Venturi, short-form Venturi, eccentric form Venturi, and rectangular Venturi. In cases of large ducts, rectangular Venturi tubes are common. In the case of a large duct (air/gas), a Venturi with piezometer rings is also used. Venturi tubes find use in slurry flow with purging, but in such cases piezometer rings are not used.

4. **Dall tube (flow tube):** ASME defined a broad category of differential pressure-producing elements whose designs differ from Venturi tubes. Tee Dall tube is one of those categories. These proprietary primary head type devices have a higher ratio of pressure developed to pressure lost than a Venturi tube [12]. Another important issue here is that as there are several proprietary head type flow elements, they naturally have different differential pressures and head losses for a given flow as per the manufacturer calculations and assumptions. For this reason it is necessary that the manufacturer supply all necessary data and drawings for verification. A Dall tube normally has a flanged spool piece body with a short, straight inlet section terminating in an abrupt decrease in diameter (shoulder). This is followed by a

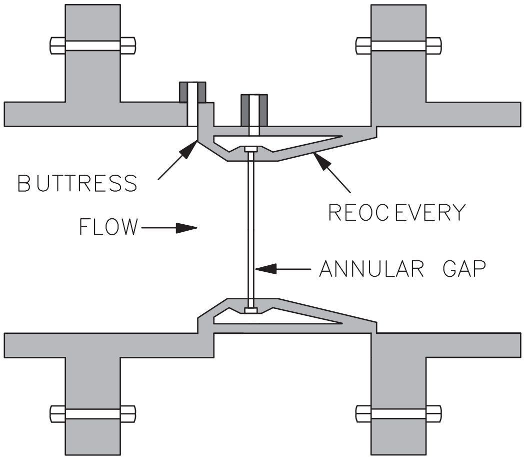


FIGURE I/3.1.1-4 Dall flow tube. *Courtesy of Instrumentationtool.com.*

conical restriction and diverging outlet with a narrow annular gap as depicted in Fig. I/3.1.1-4. The distance between the front face and the tip is nearly half the pipe diameter. As shown, the high-pressure and low-pressure tapping points are located at the inlet shoulder and the annular gap in the throat, respectively.

Very small head losses and availability in various short sizes are advantages of the Dall tube. It has high straight length requirements as it is highly sensitive to upstream disturbance on account of the tapping location being in the upstream side.

5. **Pitot tube:** This is a low-cost DP element, frequently used in low head air flow measurements such as HVAC. Basically this element works on the principle of converting kinetic energy into potential or pressure energy. When a stream of fluid approaches or strikes a centrally placed stationary solid body held in a pipeline, the fluid stream loses its velocity to zero directly in front of the body. This is the stagnation point. On losing the kinetic energy, the fluid stream gains a static head. In a Pitot tube type flow measurement two pressures, impact and static, are sensed. The impact unit consists of a tube with one end bent at right angles toward the flow direction. The static tube's end is closed, but a small slot is located in the side of the unit [26]. The tubes can be mounted separately in a pipe or combined in a single casing as shown in Fig. I/3.1.1-5. It is easy to install the element into a pipe or duct (even in an existing plant). The DP

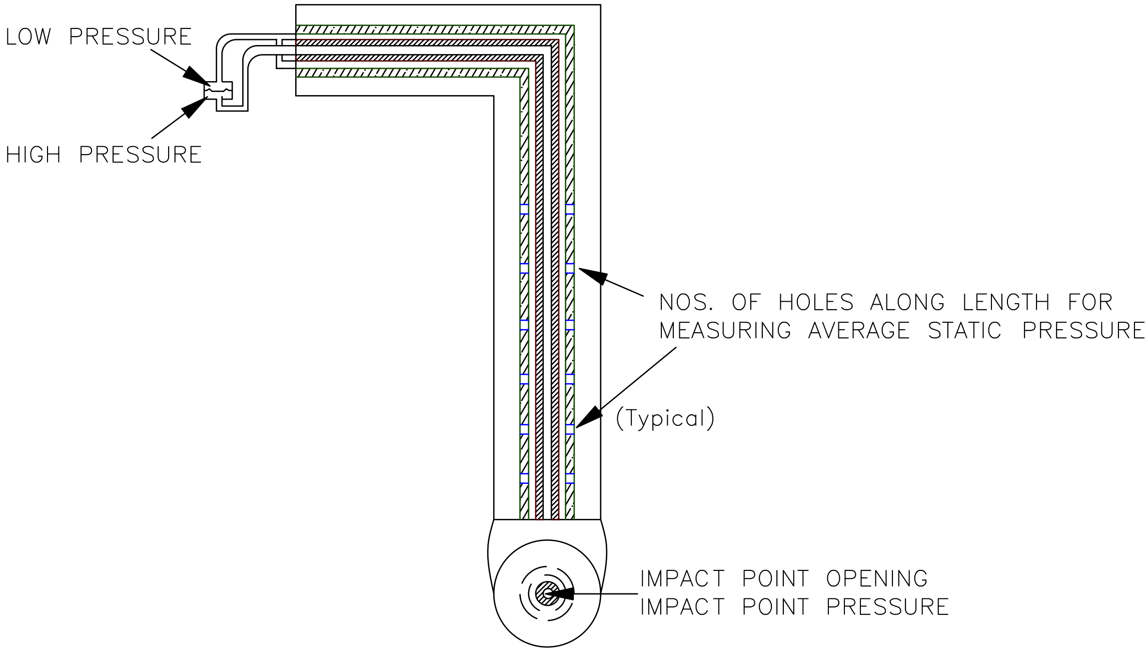


FIGURE I/3.1.1-5 Pitot tube.

between the pressure due to impact and the static pressure are used to compute the average velocity and hence the flow. The Pitot tube causes practically no pressure loss in the flow stream but certain characteristics of Pitot tube flow measurement have limited its industrial applications [27]. It has the problem of getting blocked frequently, and so is not suitable for dirty liquids/gas. The Pitot tube is frequently used to measure air (primary air) flow in a boiler.

6. **Annubar:** There is not much difference between a Pitot tube and Annubar. Fig. I/3.1.1-6 shows the basic principles of measurement. It is also known as an average Pitot, but in this book it will be dealt with separately in Chapter II.

   An Annubar may be conceived of as several Pitot tubes placed across a pipe to obtain an approximation to the velocity profile, and the total flow can be calculated based on the difference of average upstream pressure and downstream pressure measurements. At the leftmost part the velocity profile and associated changes in upstream pressure have been shown. Where there is highest velocity at the center the change in pressure due to obstruction is the highest (and has a lesser impact towards the wall where the velocity is also lower). Thus there will be a high-pressure profile—produced by the impact of the flow velocity profile on the upstream side of the sensing tube. The flow that passes through the sensor creates a low-pressure profile [27]. Two-chamber flow tubes with several pressure openings distributed across the stream are shown in Fig. I/3.1.1-6. This annular averaging element is called an Annubar [27]. An Annubar flow sensor produces a DP signal that is the algebraic difference between the average value of the high pressure and low pressure. Averaging Pitot tube (APT) technology reduces the total cost of ownership of flow measurement by lowering the installation and energy costs. Like a Pitot tube, an Annubar also contributes very small pressure drops. It has limited accuracy and like a Pitot it is prone to blockage and hence is not suitable for measurement of liquid that contains dirt. It finds its use in air flow measurements in boiler plants.

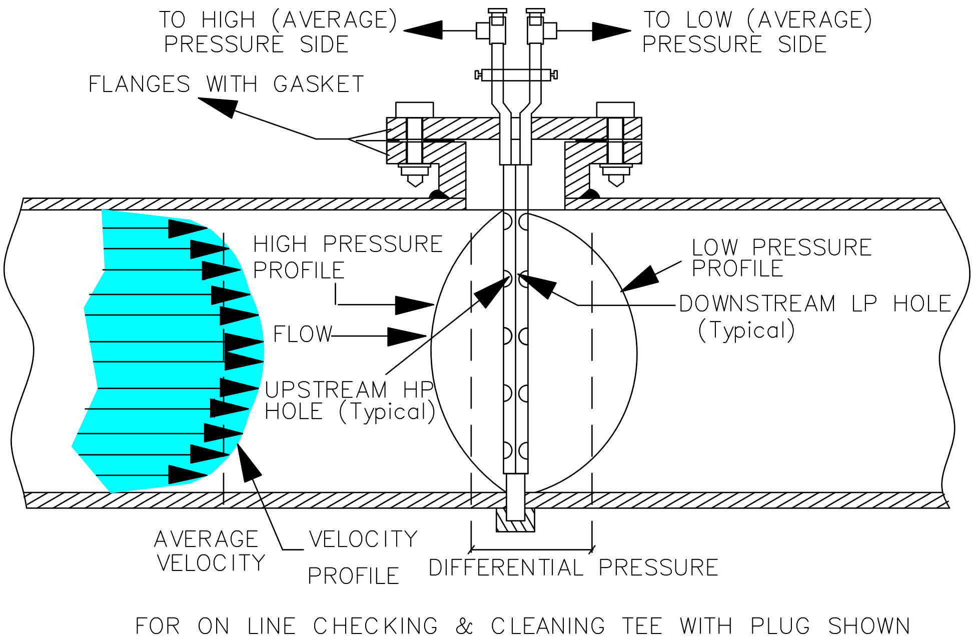


FIGURE I/3.1.1-6 Annubar.

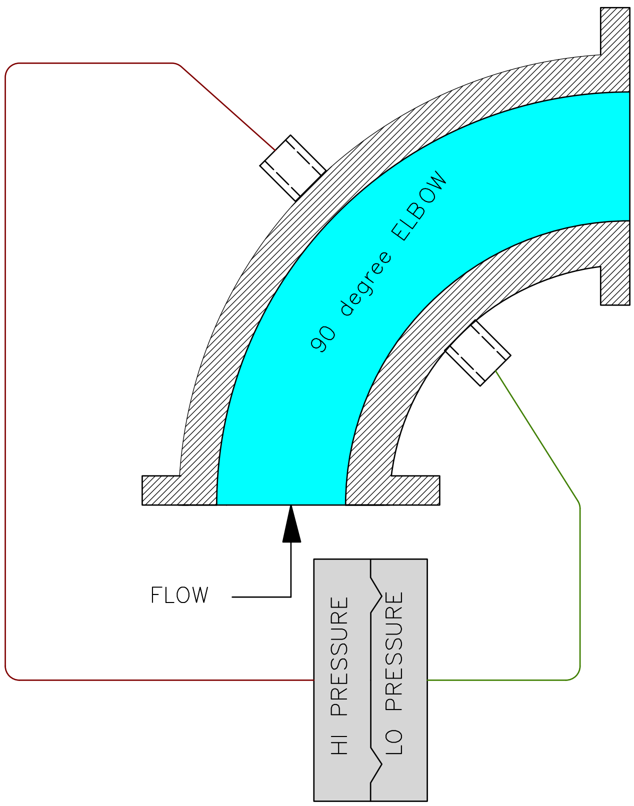


FIGURE I/3.1.1-7 Elbow tap.

7. **Elbow tap:** As stated earlier the DP is not generated due to restriction but due to centrifugal force. A typical 90 degrees elbow tap meter is shown in Fig. I/3.1.1-7.

   The meter operates within the general physics principles. When a fluid moves in a curved path there will be a centrifugal force due to the acceleration of the fluid. From basic physics it is know that centrifugal force is given by mv^2/R (m = mass; v = velocity; R = radius). Naturally, on account of the higher "R," there will be less velocity in the outer side and so to balance energy there will be more pressure (potential) energy than on the inner side with a smaller "R." This will cause a differential pressure between the outside (higher pressure) and inside (lower pressure). Thus a differential pressure exists when a flowing fluid changes direction due to a pipe turn or elbow (see Fig. I/3.1.1-7). Taps are located at 45 degrees for a 90 degrees elbow (see Fig. I/3.1.1-7). As pipe elbows are common in plants there is no cost for restriction elements, and so measurement is less costly. Also, it does not cause any added pressure loss. However, the accuracy is very poor (not less than 4% FSD) and it is not suitable for low-velocity fluid flow. From this one can infer that when this elbow is used in a size smaller than the pipe size with a reducer, then the velocity will increase and it is possible to get a better DP. When applying this measurement in liquids containing dirt, then there is the possibility of a line blockage for which a purging method may be utilized.

8. **Wedge meter:** The discussions on wedge meters start with Fig. I/3.1.1-8, where it

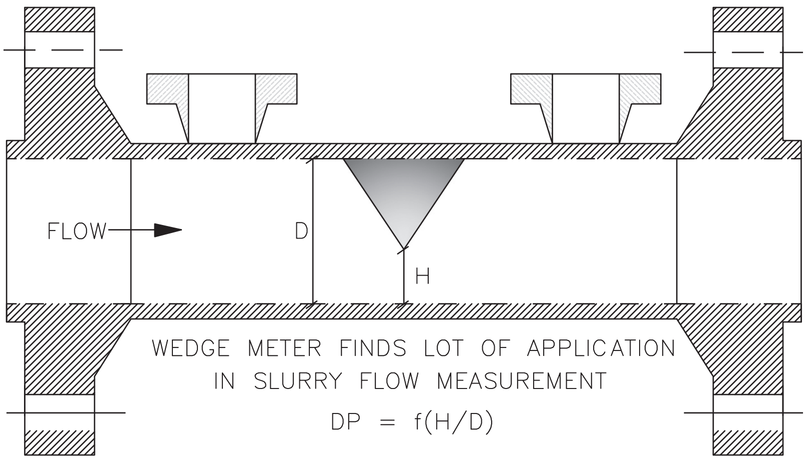


FIGURE I/3.1.1-8 Wedge.

can be seen that the element consists of a V-shaped wedge (restriction) on the top side of the meter.

The slanted faces of the wedge meter provide a self-scouring action [25]. These meters are suitable for liquids with suspended solids and slurry flow and viscous fluids. However, accuracy, head loss, etc. are inferior to a Venturi tube [28]. Like other DP-based elements, here also a DP is generated due to restriction, but it is of a different type. Here a constriction wedge is fabricated on the top part and is behaviorally somewhat similar to a segmental orifice. However, here the fluid is guided along a sloping "wedge" shape rather than a sharp edge [29]. The differential produced is a function of the ratio of diameter "D" and wedge height "H," as shown. The pressure taps are located upstream and downstream of the wedge. It is available from as low as 25 to 800 mm. Wedge meters are inherently robust, requiring less maintenance.

9. **V-one device:** The V-cone device meter is well recognized for its greater accuracy (up to ±0.5% of the rate) and repeatability, and wider rangeability when compared to an orifice plate as a flow element. It also offers installation flexibility and reduced maintenance. As stated earlier, it can be used for very difficult flow conditions from very low to extremely high Reynolds numbers or measuring swirling fluids or low-pressure flows [30]. A V-cone flow device, shown in Fig. I/3.1.1-9, can be used for both dirty as well as clean fluid measurements.

   In comparison to an orifice it has better permanent pressure loss. This is a DP type flow element, one tapping (static pressure) is taken slightly upstream of the cone with the other tapping located in the downstream face of the cone itself. The design incorporates a contour-shaped cone at the center of the pipe with annular passages which direct the flow without impacting it against an abrupt surface, thus avoiding wear of edges of the cone by dirty fluids. Because of this feature, recalibration of V-cones is rarely required [24]. They are available in different sizes from 15 to 3000 mm. A brief comparison with an orifice plate is presented in Fig. I/3.1.1-9. Operating principles have been elaborated in Chapter II (Section 8.1.1) for deriving the flow formula and sizing.

10. **Rotameter:** A rotameter and piston meter are two types of flow meters that fall under the category of variable area meters. Rotameters are the most popular and are discussed here. A rotameter is a kind of inferential flow meter, but metering is not carried out by DP measurement. This inexpensive flow meter provides practical flow measurement solutions for many applications. A rotameter basically consists of a tapered metering tube and a float that can freely move within the tube, there may be an outside casing and means for remote transmission also if applicable. This flow metering is a linear function of flow rate. In the case of no flow, the float, which usually has a diameter the same as the bore of the flowing tube, rests freely at the bottom of the tube. When fluid enters from the bottom of the tube, the float begins to rise. The float material has a higher density than the fluid and the position of the float varies directly with the flow rate. During flow, buoyancy helps the float into the upper position, but this force is insufficient due to float weight. At a particular flow rate the upward flow and float weight and buoyancy forces are balanced to give a direct reading. At higher flow, the float moves up so that there will be more force due to pressure multiplied by the increased area of the tube. The up- and downward movement of

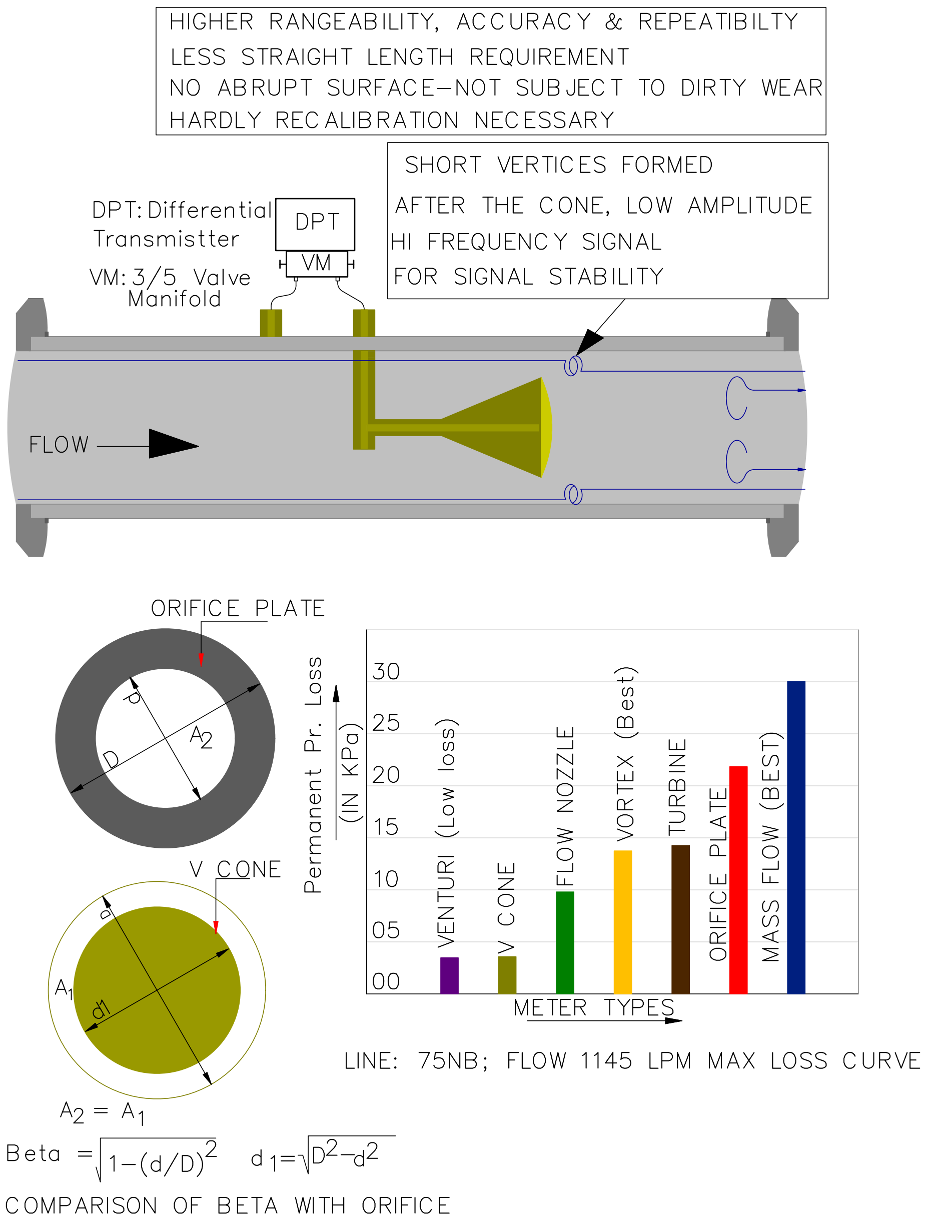


FIGURE I/3.1.1-9 V-cone device. *Based on and courtesy of McCrometer Permanent Pressure Loss Comparison Among Various Flow Meter Technologies, McCrometer; White Paper; S. Basu, A.K. Debnath, Power Plant Instrumentation and Control Handbook, Elsevier, November 2014, http://store.elsevier.com/Power-Plant-Instrumentation-and-Control-Handbook/Swapan-Basu/isbn-9780128011737/.*

the float is proportional to the fluid flow rate and the annular area between the float and the tube. A typical rotameter has been depicted in Fig. I/3.1.1-10. Rotameters can offer an accuracy of ±2% of FSD, and are available in various sizes. Some rotameters may also have facilities for remote transmission.

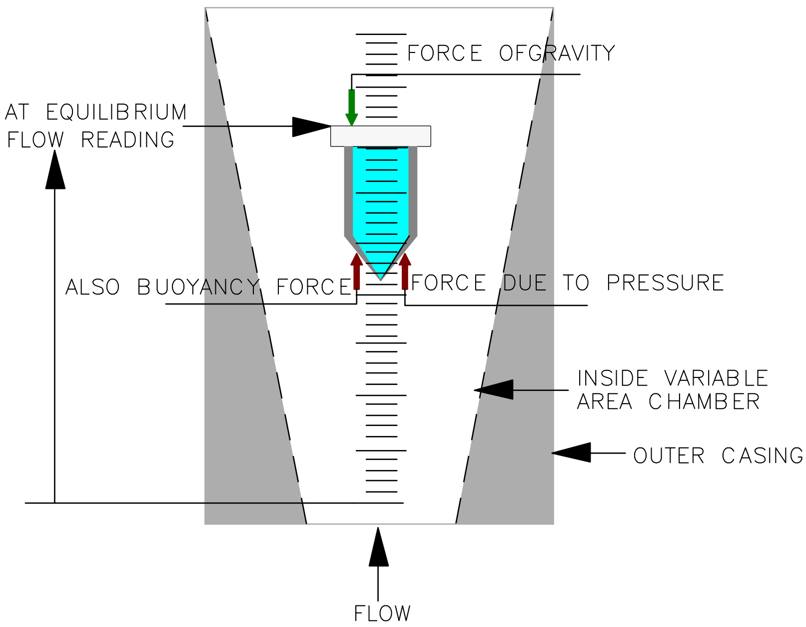


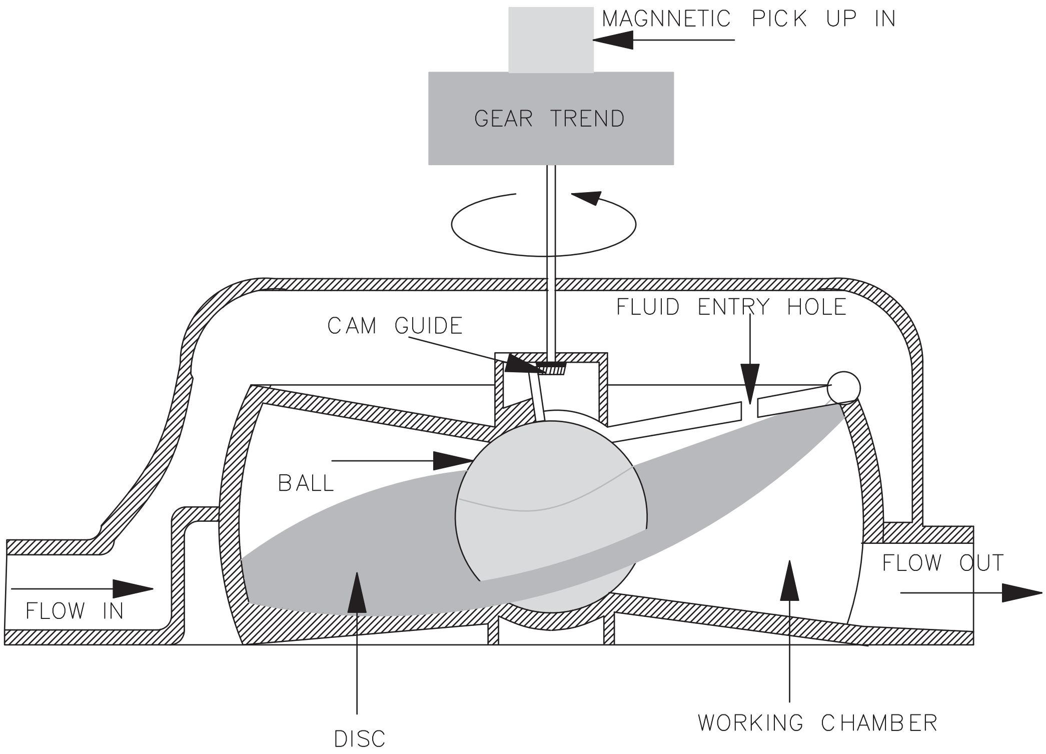
FIGURE I/3.1.1-10 Variable area rotameter.

3.1.2 POSITIVE DISPLACEMENT FLOW METER TYPES AND PRINCIPLES

Positive displacement (PD) flow meters are mechanical type flow meters with moving parts. They are deployed for direct measurement of volumetric steady flow of fluids. Here the volume is not calculated but measured directly. Accordingly, fluid velocity, pipe inside diameters (IDs), and flow profiles are not a concern [25]. In positive displacement flow meters, the mechanical moving parts are located in the flow stream to physically separate the fluid into separate known volumes based on the physical dimensions of the meter. These known volume increments are counted or totalized [27]. For this reason many of these meters are available with a flow totalizing counter (mechanical). Linear motion or counting the number of cycles of rotation provides the displaced fluid. These flow meters are used for volumetric flow in a wide range of nonabrasive fluids, including high-viscosity fluids. Accuracy may be up to ±0.1% FSD. This type of meter also offers high rangeability of the order of 65:1 or better. Higher pressure drop and higher cost of installations and maintenance (moving parts) are some of the demerits of this type of flow metering. These are not suitable for solid flow measurements but are very good candidates for measurement of volumetric flow of highly viscous fluids (possibly with low electrical conductivity, e.g., oil applications). PD meters are often used as domestic water meters because PD meters are integrating type meters. With reference to Fig. I/3.1.0-2, the discussions on PD meters start with discussions on the nutating disc.

1. **Nutating disc:** Fig. I/3.1.2-1 shows a schematic diagram of a flow meter. As shown in the figure there is one disc assembly. The movable disc assembly consists of a radial slotted disk with an integral ball and an axial pin. As shown in the figure there is one disc assembly.

   The position of the disc divides the working chamber into compartments, one above and one below the disc. These chambers are filled and emptied successively, each compartment holding a definite volume. Fluid (liquid) enters the meter through an inlet of the meter and passes upward into the top of the main casing. The fluid also acts as a lubricant for the internal gearing, etc. in the top casing part.



SCHEMATIC DRAWING NOT TO SCALE

FIGURE I/3.1.2-1 Nutating disc.

The fluid enters the working chamber through a hole as shown. On entering the measuring chamber, it drives the single *measuring disc* which nutates and the fluid (liquid) goes to the other part of the chamber. The positive displacement *cam* compels it to make a complete nutation at each movement. So, with the help of this complete nutating motion, fluid comes in and goes out to the outlet port each time with a definite volume. The complete nutating motion is transmitted by a gear train to the totalizer or pick up for the pulse transmitter. It is very popular as a domestic water meter. It provides an accuracy of 1%−2% FSD. The maximum pressure- and temperature-withstand capability of the meter are about 10 kg/cm^2 and 150°C, respectively.

2. **Oval gear:** In an oval gear meter, two oval gears are placed and mechanically interlocked by 90 degrees in the meter housing. These gears are rotated by the flowing fluid. When the two oval gears are rotated by fluid (liquid) a defined volume of fluid is transported from the inlet through the meter to the outlet. These oval-geared meters are generally used on high viscous liquids. Fig. I/3.1.2-2 shows the flow of fluid (liquid) in the bottom part of the meter. Similarly there will be flow from the top part also. As shown in the schematic (Fig. I/3.1.2-2), there are various stages of movement of fluid. In the figure only one part of the flow has been shown to understand the principles of operation. A definite volume of liquid is captured by the gap formed between the housing and the gear. In the first position there is a force on the bottom of the upper gear which causes it to rotate clockwise (CW). This causes the bottom gear to rotate in a counterclockwise (CCW) direction to the position shown in the next figure.

   In this position a definite volume of fluid is trapped in the bottom part (the bottom part

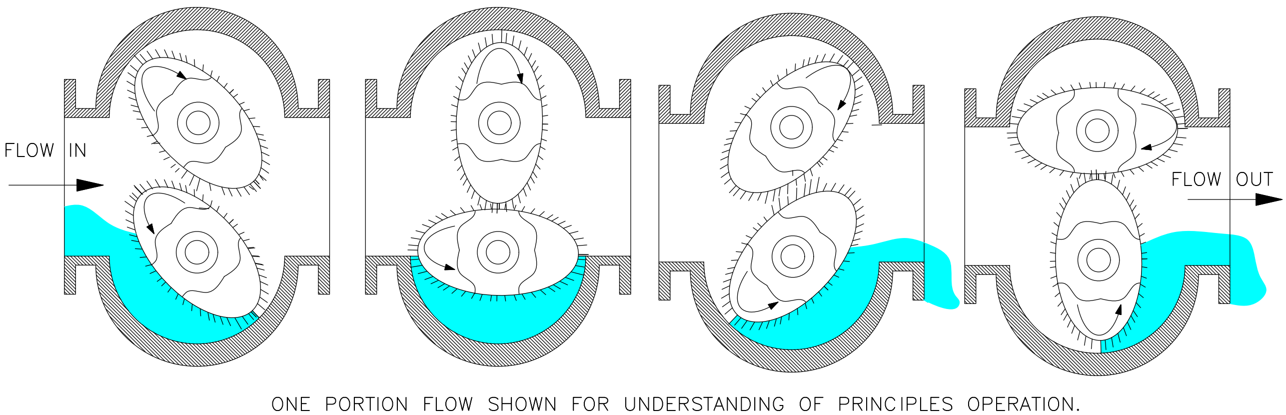


FIGURE I/3.1.2-2 Oval gear.

only is shown and discussed here). Now the fluid in the inlet side puts force on the top gear which causes the bottom gear also to move so that part of the entrapped fluid is discharged. At this time fluid in the inlet side puts force on the bottom gear in the lower part and the top gear in the upper part and because of the two different directions of movement (CW and CCW) the entire volume is discharged by the bottom gear in the last figure. Similarly, there will be flow from the top part also (not shown). Magnets are often fitted at the rotor, and with the help of these magnets and reed switch contacts often pulses are created and measured. At times these are converted to 4–20 mA DC by converters. This type of meter is available in various sizes from 6 to 600 mm (or even larger sizes) and offers high accuracy, in the order of 0.1% FSD or better. However this meter is only suited for clean fluids.

3. **Rotating piston:** The principles of operation of a rotating piston flow meter have been detailed in Fig. I/3.1.2-3. The measurement chamber is cylindrical with a partition separating its inlet port from its outlet. Liquid enters into a machined chamber containing an oscillating piston. The position of the piston divides the chamber into compartments containing an exact volume [32]. Fluid pressure then causes the oscillation of the piston about the central hub. The movements of the hub are sensed through the meter wall by a series of magnets.

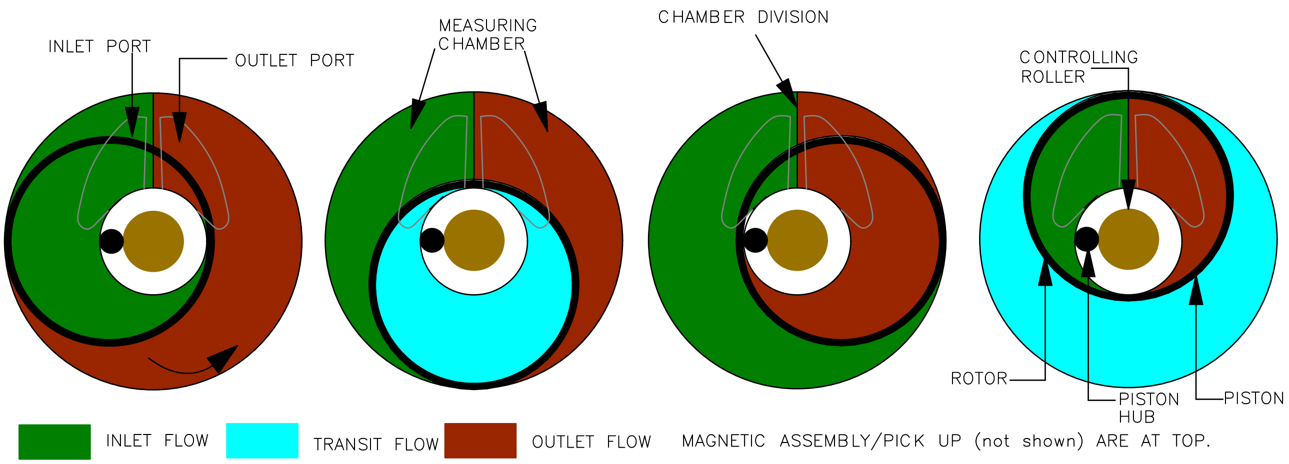


FIGURE I/3.1.2-3 Rotating piston.

As shown in the figure, upon entry of fluid into the measuring cavity from the inlet, a differential pressure will be formed which causes the piston to rotate in a CCW direction. Accompanied with liquid flowing in, the piston will rotate to the location as shown, forming an enclosed volume. Under the action of differential pressure, the piston will continue rotating and as a result the enclosed volume will gradually open to the outlet and begin to discharge liquid as shown. For better understanding, three separate sets of fluid volumes are shown in color (green: inlet; maroon: outlet; cyan: transitional flow). The piston is guided by a control roller within the measuring chamber. In this way, piston rotation will continuously cause liquid to pass through the flow meter and volume flow of every cycle will equal the amount of measuring cavities. Therefore, it is seen that each revolution of the piston hub is equivalent to a fixed volume of liquid, which can be transmitted as a pulse count with the help of magnetic pick up for remote transmission and/or for totalizing. As stated earlier, the motion of the piston is transferred to a follower magnet which is external to the flow stream. The motion of the piston is oscillatory (not rotary) since it is constrained to move in one plane [32]. Meters are available in various sizes to cater to the flow range from 0.7 to ~300 L/min (LPM). It is also available for high-pressure applications. A very high turndown ratio of >300:1 is also possible. It offers accuracy better than 0.5% of the actual reading.

4. **Rotating vane:** A rotating vane is another type of PD meter. It basically has two options, one with a cam and the other without a cam. Both versions are depicted in Fig. I/3.1.2-4. The first set is for a meter with a cam. The other is with an eccentrically mounted rotor. However, the basic operation principle is the same.

The principle of operation of the meter is similar to what has been discussed so far. The basic unit consists of rotating impellers (two or more) mounted inside the meter housing. These impellers divide the entire space into two/four equally divided compartments as shown in Fig. I/3.1.2-4. When fluid appears at the inlet it pushes vane 1 to a change position. A naturally fixed quantity of fluid in the measuring chamber shown is pushed out, and partly goes to the outlet. Next vane 2 is rotated. Here one thing to be noted is that one set of impellers (two impellers) is in

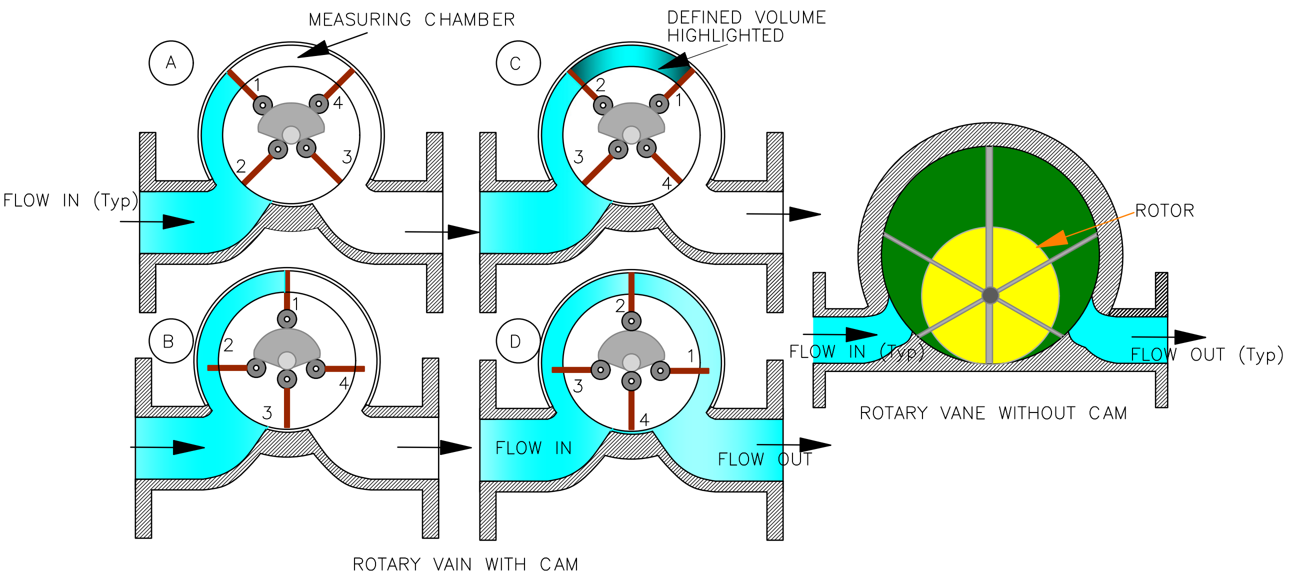


FIGURE I/3.1.2-4 Rotating vane.

continuous contact with the casing to deliver a fixed volume of liquid from the inlet to meter's outlet, from each compartment as the impeller rotates. From the figure it can be seen that in the first position (A) the impeller set comprising 1 and 4 is touching the casing to ascertain the volume and in positions B, C, and D the impeller sets are 1−3, 1−2, and 2−4, respectively. This is possible because of the cam shown. There are other versions without a cam, where spring-loaded vanes are used, along with the eccentrically mounted rotor to entrap liquid between the casing and vane as shown in the right hand side of Fig. I/3.1.2-4. Normally, a Hall sensor and magnets are used to sense the rotary motion of the vane for totalizing, and/or converting to mA signal. The meters are available with a high turndown ratio >50:1 in the range of 20−1900 LPM.

5. **Other PD meters:** There are a few other types than those already discussed.

- *Reciprocating piston:* A reciprocating piston flow meter is quite a popular PD meter. Many put this meter and rotating piston under the common heading of a piston type flow meter. A typical reciprocating piston meter has been detailed in Fig. I/3.1.2-5. In this type of flow meter the flow piston movement makes the fluid pass through alternately between the two sides of the piston with the help of a sliding valve with both the inlet and outlet in open positions (shown).
- *Helical gear type:* This meter is named after the shape of the gear which is like a helix (spiral-shaped). The helix flow meter is a positive displacement device utilizing two uniquely nested, radically pitched helical rotors as the measuring elements [27]. When the fluid passes through the meter it enters the compartments containing rotors which start rotating as the flow passes by. The rotation of the gear is proportional to

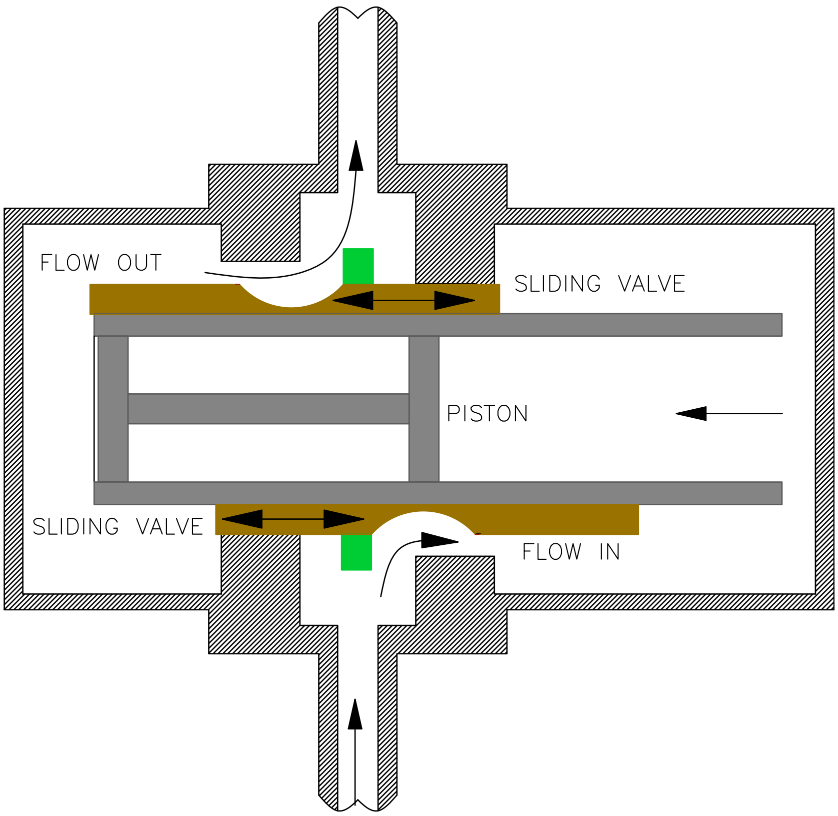


FIGURE I/3.1.2-5 Reciprocating piston.

flow (as it passes through a fixed-volume chamber), so the rotation flow can be computed. These are used for paint spray and material manufacturing. They introduce less of a pressure drop. With this, discussions on PD meters come to an end to see how flow can be measured with velocity and force sensing.

3.1.3 VELOCITY AND FORCE FLOW METER TYPES AND PRINCIPLES

There are a number of meters which deploy the means to measure the average velocity of the flowing fluid inside a pipe then multiply the same with the area inside the pipe to compute the volumetric flow. As in this case there is no square rooting, and normally high rangeability is possible. While specifying the average velocity of the fluid, operators should be concerned with the velocity profile of the fluid, which, as was seen earlier, is a function of pipe geometry and Reynolds number. Again the Reynolds number is dependent on viscosity, density, etc., so selection of average velocity from the velocity profile is of prime concern. For Reynolds number >10,000 the velocity meter is highly sensitive to changes in viscosity. Another important issue here is the straight pipe length requirement of the flow meter duly recommended by manufacturer, so as to achieve the required accuracy. In the majority of process and chemical plants typical velocity values for *liquids* lie between ***0.15*** and ***<4 m/s*** (0.5 to <13 ft/s), whereas in the case of *gas* it could be **4.5** to <**65 m/s** (15 to <215 ft/s) [25]. In most cases the velocity type flow meters are fitted with flanges so that these can be fitted in line with the pipe [26]. There are a number of types of flow meter falling under this category, and the majority of them which are commonly used in industrial applications will be covered here. A turbine flow meter is often referred to as an inferential flow meter as it can compute totalized flow from a velocity computation. Also, the Coanda effect and momentum exchange flow meters are often referred to as "*oscillatory*" or "*fluidics*" (see Fig. I/3.1.3-8) flow metering. A target flow meter (see Fig I/3.1.3-7) is really the odd man out here! The target type flow metering principle depends on the force created on the target due to the pressure of the flowing fluid in the pipe. This discussion starts with velocity type flow meters.

1. **Turbine flow meter:** Turbine flow meters have found widespread use for liquid measurements and are available in sizes from 5 to 700 mm with good pressure and temperature ratings. As the name suggests this meter contains a turbine against which the fluid flows, causing turbine blades to rotate at a speed proportional to the velocity of the flowing fluid. The turbine meter usually comprises an axially mounted multiple-bladed rotor assembly duly supported. The rotor is supported by ball or sleeve bearings on a shaft which is retained in the flow meter housing by a shaft-support as shown in Fig. I/3.1.3-1. The rotor assembly is placed in a pipe with its face perpendicular to the liquid flow. The rotor assembly (the turbine) runs on bearings. As the liquid passes through the blades, the rotor rotates at a speed which is a direct function of velocity, hence flow rate and can be sensed by magnetic pickup, photoelectric cell, or gears. Here magnetic pick up has been shown. A simple tachometer could be used to measure the speed to compute flow. For low-viscosity fluids it offers very high accuracy. A major issue is the wearing of the turbine bearings. There has been development in turbine meter design to have turbine meter with fluid coupling.

   The simplest method for measuring the rotor speed is by means of a magnet in a rotor assembly as shown in the left side of Fig. I/3.1.3-1 so that a single pulse per revolution is available in an externally mounted pickup. For better reading resolution, in practice, the speed of rotation is monitored in most of meters by a magnetic pick-up coil, fitted outside the meter housing. The magnetic pick-up coil consists of a permanent magnet with windings placed at close proximity to the rotor (external to the fluid path) As the rotor blades, which are made of a magnetically permeable ferrous

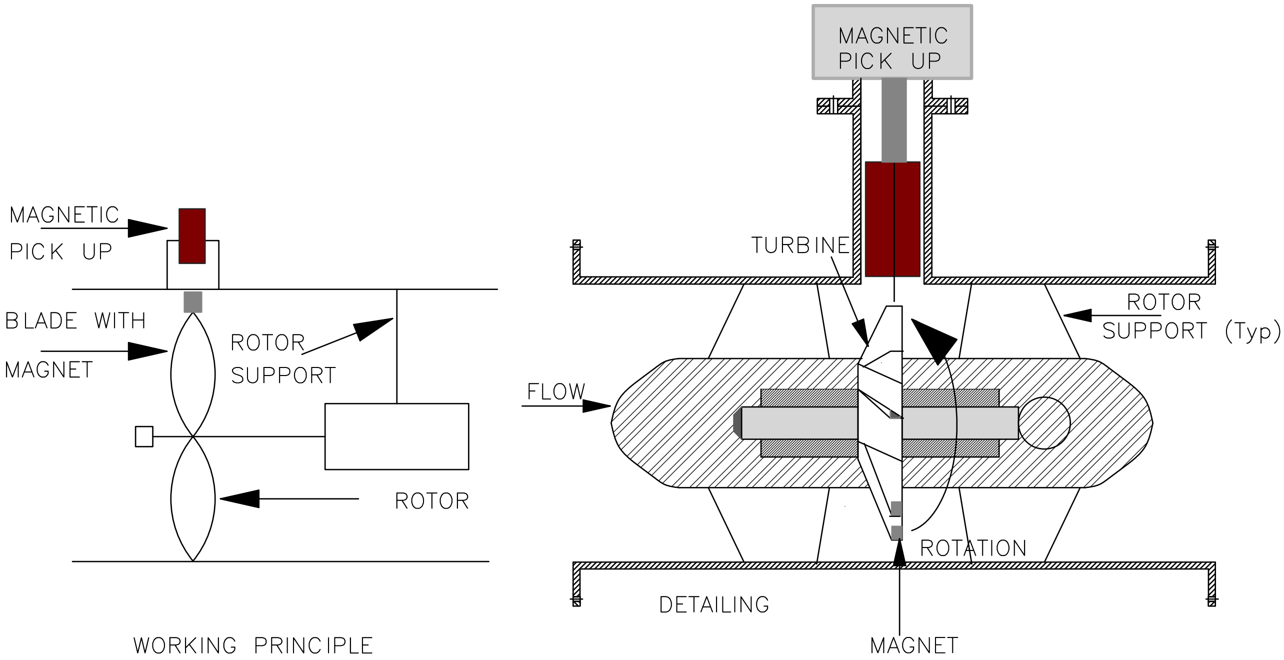


FIGURE I/3.1.3-1 Turbine (flow meter).

material [5], pass the magnetic pick-up coil, it generates a voltage pulse which is a measure of the flow rate. Totalized flow can be computed by the total number of pulses utilizing digital techniques. It can provide high accuracy, e.g., 0.25% FSD, rangeability of >10:1, and easier installations and maintenance. However high-cost, nonsuitability in nonlubricating fluids, and slurry applications are major disadvantages. Also, for gas flow measurements it normally requires a flow conditioner placed upstream with 10D & 5D up- and downstream straight length requirements.

2. **Vortex and swirl flow meter:** Vortex shedding in fluids occurs naturally also, e.g., fluttering of a flag on a flag pole, or the whistling tone that the wind produces through telephone wires, etc. In all such cases it can be noted that the intervals between vortices is constant and is only a function of the diameter of the flag pole. When an obstruction (nonstreamlined object) is placed in the path of a flowing stream with high Reynolds number, the fluid cannot remain attached to the object on its downstream sides and will alternately separate (shed) from one side. The slow-moving fluid in the boundary layer of the body becomes detached on the downstream side to form eddies and vortices (see Subsection 1.2.2.6). On the side of the bluff body, where there is vortex shedding, the fluid velocity increases and consequently the pressure decreases. On the opposite side, the pressure increases and velocity decreases. This will cause a net pressure change across the bluff body. The entire effect is then reversed as the next vortex is shed from the opposite side. Therefore, the velocity and pressure distribution adjacent to the bluff body change at the shedding frequency. It has been noted that the distance between the shed vortices is constant, regardless of flow velocity. This principle is called Karman's principle. Vortex meters make use of this natural phenomenon, which occurs when a fluid (with *high* Reynolds number) flows around a bluff body (*a bluff body is defined as a body with a cross-sectional shape that offers large resistance to incoming flow to retard it*). Vortex shedding flow meters are applicable for fluid flow with high Reynolds numbers only. In building a vortex flow meter, the manufacturer usually selects an obstruction

width (d) that is one-quarter of the pipe diameter (ID). As long as the bluff body is not eroded or coated and the Reynolds number is high, the meter measures the flow in terms of velocity of the fluid, by measuring the frequency of vortex shedding [12]. Typical velocity measurement for vortices in a bluff body and vortex flow meter has been depicted in Fig. I/3.1.3-2.

There could be a number of means for detecting the flow, some of them are listed here.

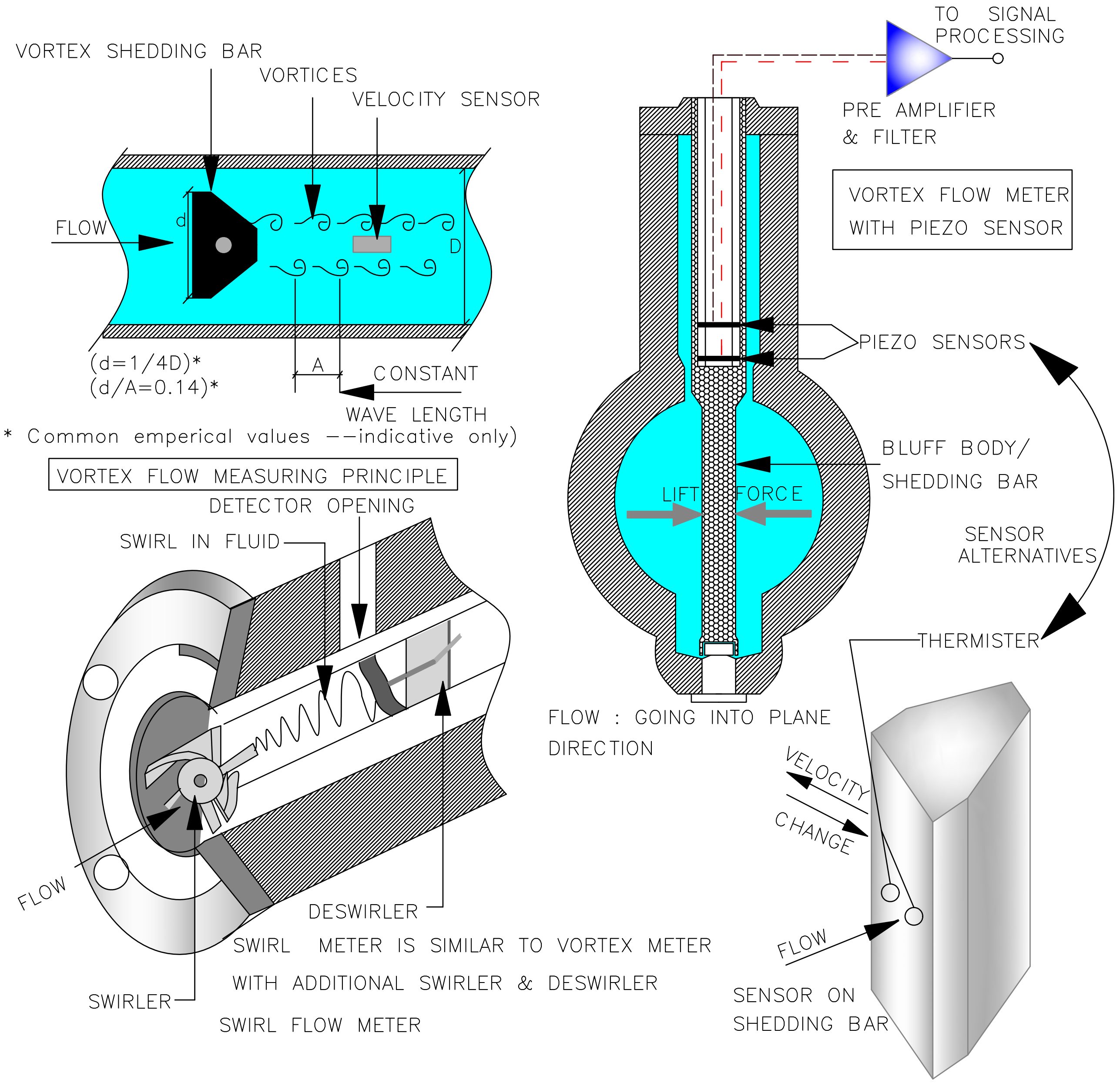


FIGURE I/3.1.3-2 Vortex and swirl. *Based on an idea from Instrument Engineers' Handbook, vol. 1: Process Measurement and Analysis, CRC Press (Chapter 2 Flow Measurement and Chapter 1.4 System Accuracy); ABB Flow Meters; Review of Industrial Processing Flow Meters, ABB White Paper, http://www.tundrasolutions.ca/files/ABB%20Flowmeters%20Review%20of%20industrial%20processing%20flowmeters.pdf; General Specification; DY Vortex Flow Meter; YEWFLO, Yokogawa, http://web-material3.yokogawa.com/GS01F06A00-01EN.pdf.*

- The oscillating flow across the face of the bluff body.
- Differential pressure across the sides of the bluff body.
- Flow through a passage drilled through the bluff body.
- Flow or pressure at the rear of the body.
- Detection of free vortices downstream to the bluff body. Flow sensing could be electrically heated, e.g., using a thermistor or a magnetic shuttle. Ultrasonic sensors (passive ultrasonic sensors) can be used for counting vortices. Pressure-sensitive detectors could be piezoelectric sensors, capacitive sensors, or strain gage sensors (like those in pressure transmitters). Pressure sensors are aided by a metal diaphragm. A typical piezo sensor mounted (e.g., YEL vortex meter) on a shedding bar has been depicted in Fig. I/3.1.3-2. In such meters the shedding bar is subject to alternate lifts at the vortex shedding frequency. This alternate lifting creates changes in the stress in the shedding bar and is detected by a piezo sensor.

Swirl flow meter operation is similar to that of a Vortex flow meter, as it is a patented flow meter. In a swirl meter, a set of blades welded at the inlet of the meter body is called the swirler (as in turbine blades), which imparts a tangential velocity (or swirl) to fluid flowing to it. Swirl flow meters combine the advantages of turbine and vortex flow meter technologies. They have a high turndown ratio (30:1) and high accuracy [34]. In the case of vortex meters, often flow meters are chosen in sizes less than the pipe size to get a higher velocity. However, such a requirement is not necessary for a swirl meter as it can create its own flow profile behind the swirler. It also helps in protecting the meter from damage from bubbles in liquid or liquids in gas. Near the outlet of the meter there is a "deswirler" to eliminate "the tangential velocity imparted to the fluid at the inlet and avoids affecting operation of other downstream instrumentation" [35].

3. **Coanda effect and momentum exchange:** Flow meters based on the Coanda effect (discussed in Subsection 1.2.2.9 above) and momentum exchange are referred to as fluidic meters, i.e., based on fluidics for which Fig. I/3.1.3-8 may be referenced. In this section, the application of Coanda effect and momentum exchange for measurement of fluid flow will be discussed.
   - *Coanda effect (CE) flow meter:* On account of the Coanda effect the fluid tends to stick to the adjacent walls. However, it is possible to regulate the same by the Coanda effect using an obstacle in the flow path and designing the same suitably to get a better performance designed to optimize the performance of the meter. In fluidic meters, fluid is channeled to form a turbulent jet to cause a reduction in pressure. On account of the Coanda effect, the jet will tend to be deflected from its central position and initially attach itself to one of the side walls. As stated above, the deflection by the Coanda effect is a *regulated obstacle* in the flow path. Controlling the jet path enables the formation of feedback nodes of pressure on either side of the jet. The jet can be made to oscillate by either a relaxation oscillator or commonly using a feedback oscillator as shown in Fig. I/3.1.3-3 (top part).

     The feedback oscillation principle is based on the formation of zones of different pressure either side of the jet that will control the direction of the flow. The deflected jet, in either side wall, causes a low-pressure area at the control port [12] of the chamber. The upstream part of the feedback path has higher pressure due to jet expansion as well as stagnant pressure. This causes a small portion of the main stream of the fluid to be diverted through the feedback passage to the main flow path. The feedback flow intersects the main flow and diverts it to the opposite side wall. In this way an oscillation is set in. There are mainly two chambers as

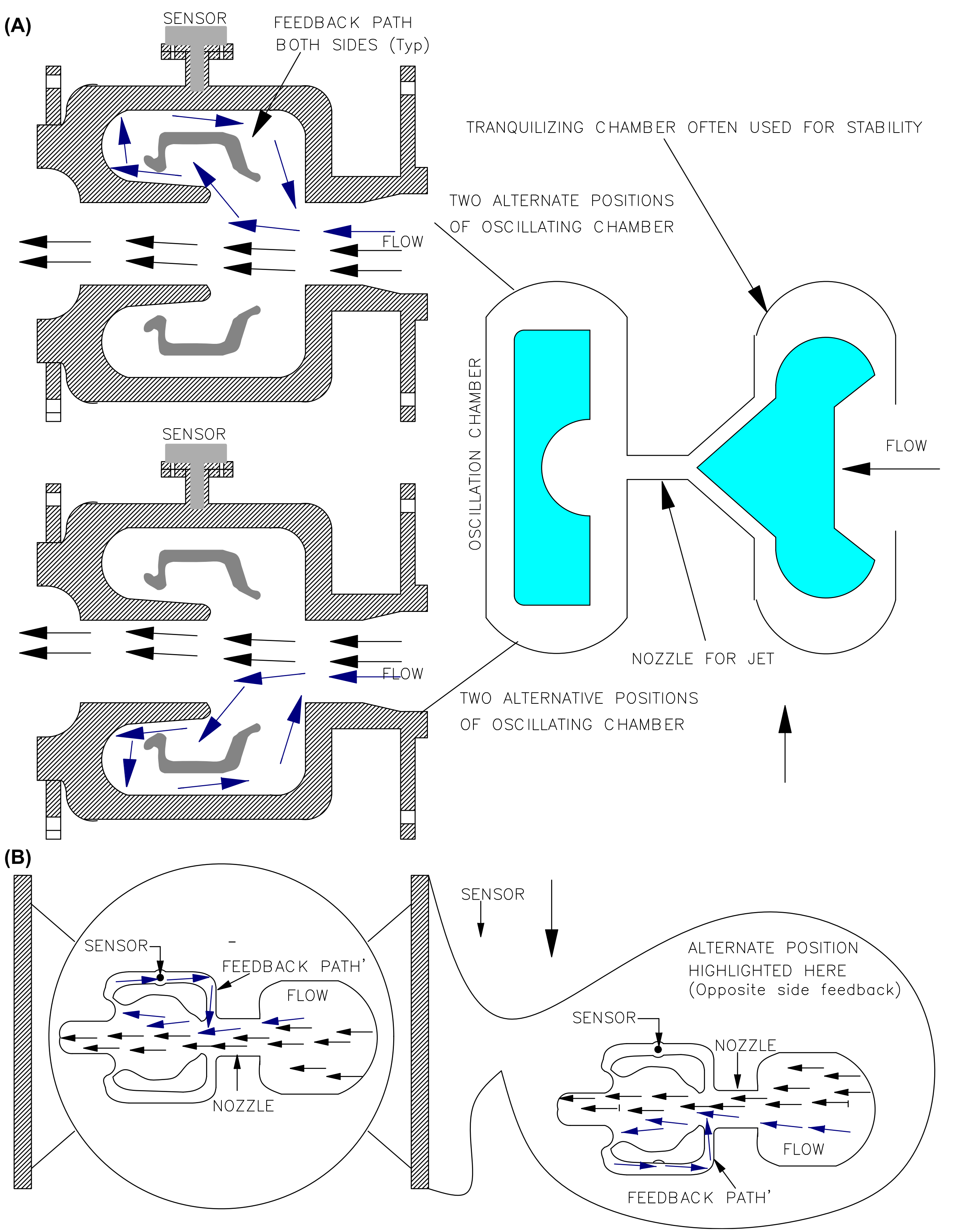


FIGURE I/3.1.3-3 Coanda effect and momentum exchange. (A) Coanda effect flow measurement. (B) Momentum exchange flow measurement.

shown in Fig. I/3.1.3-3 (top part), these are the oscillation chamber and the flow tranquilizer. In the oscillation chamber an obstacle is located in the path of the jet. The function of this obstacle is to "control" the jet and ensure the ratio of static pressure either side of the jet varies directly with the volume cycle of gas [36]. In order to eliminate the effect of any disturbance due to upstream fittings such as an elbow, etc., a piping configuration, flow tranquilizer, or flow conditioner is often used to condition the flow and to get a flow of known profile. This helps in designing the oscillator and to improve performance. For this fluidic meter to function a minimum volume is necessary and there is a minimum Reynolds number below which it does not function well. As the flow oscillates between two feedback paths so flow variations will be from 0 to maximum and the frequency of oscillation is directly proportional to the volumetric flow. Magnetic pickup or thermal sensors in either chamber or in both chambers can be used to detect the frequency of oscillation. The thermoresistive sensor detects the passage of the jet using a common mode with two elements. The two elements are positioned on either side of the gas jet [36].

- *Momentum exchange:* Typical momentum exchange flow metering has been detailed in Fig. I/3.1.3-3 (bottom part). Flow meters which are developed based on the fluid phenomenon of momentum exchange are known as momentum exchange (ME) flow meters which are similar to Coanda flow meters, but differ in the way oscillations are produced. Unlike CE flow meters, ME flow meters do not have sidewalls (or obstructions on the main jet). The geometric design of the meter body creates a main flow that passes through the nozzle and towards one side of the meter body or the other. The force of the jet of fluid will create a flow pulse in a feedback passage. The flow pulse in a feedback passage exerts a force on the main jet and deflects it so that it exerts a force on the fluid in the opposite passage as detailed in Fig. I/3.1.3-3 (bottom part). So, meters produce continuous, self-induced oscillation at a frequency that is linearly proportional to volumetric flow rate. The fluid oscillations are developed by the fluidic phenomenon of momentum exchange [37]. Like a CE flow meter there will be a sensor (of similar type discussed above in connection with the CE flow meter), on either feedback passage to detect the flow pulses.

4. **Ultrasonic meter:** Flow measurement utilizing ultrasonic energy is quite popular in industrial applications. There are three types of ultrasonic flow meters, namely, Doppler type, transit time type, and correlation type. These are detailed in the top part of Fig. I/3.1.3-4. There are another two types: the passive type and the deflection type. These are not as popular as ultrasonic flow meters (e.g., the passive type is used to count vortices).
   - *Doppler type:* From basic physics one recalls that in 1842 scientists discovered that there was a difference in the wavelength of a sound wave to a stationary listener when the source was moving toward and away from the listener. In ultrasonic noninvasive flow measurement, the Doppler principle is utilized to find the velocity of a medium by measuring the frequency shift (due to wavelength change as sound velocity is constant). In the majority of cases both transducers are placed on the same side of the pipe (refer to the second Doppler flow measurement figure in Fig. I/3.1.3-4). However, there are manufacturers who prefer to install them on two sides of the pipe wall (refer to the first Doppler flow measurement figure in Fig. I/3.1.3-4).

     In both cases, for better understanding signal flows are shown by dotted lines. Naturally, to get a reflection in most cases it depends on bubbles and suspended

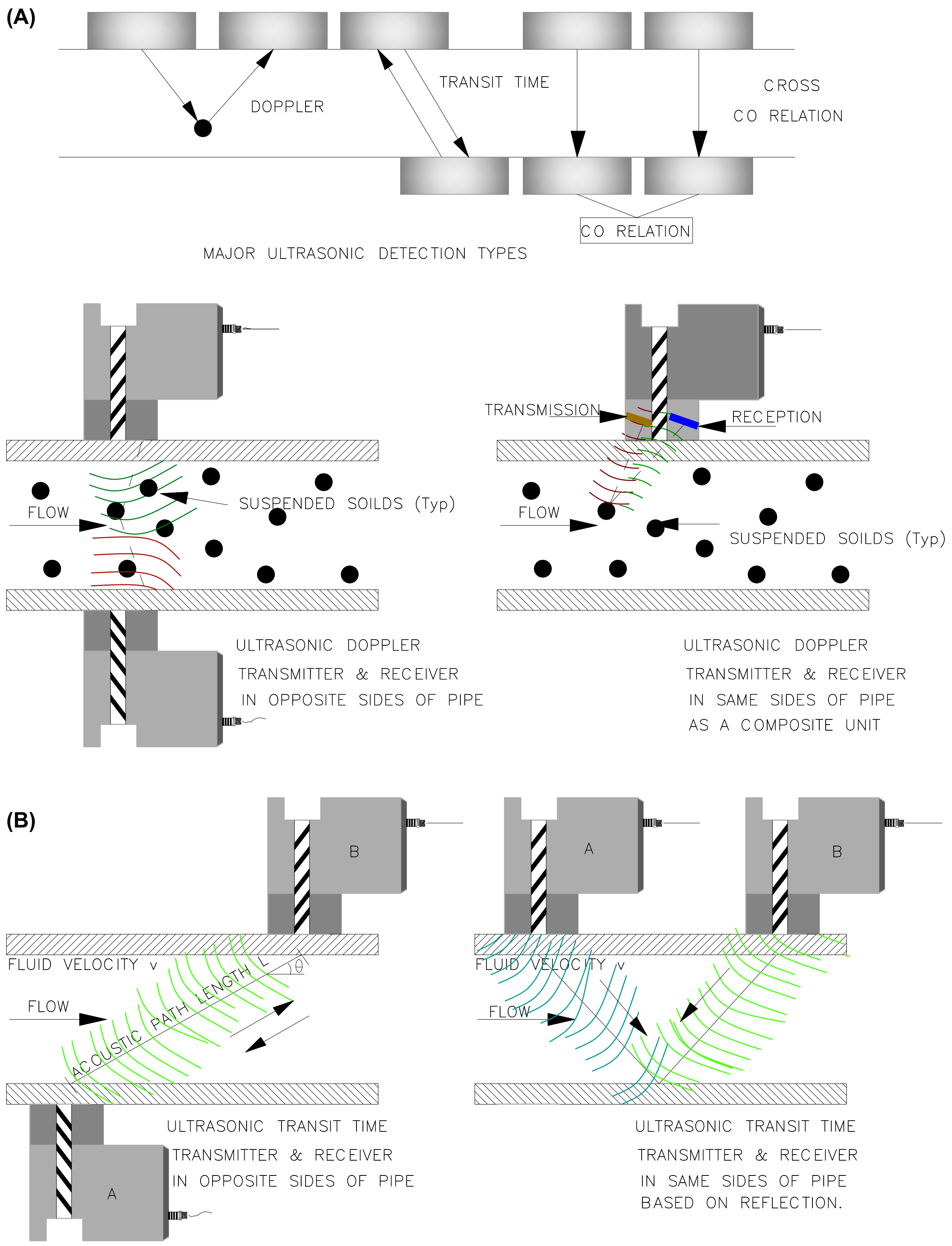


FIGURE I/3.1.3-4 Ultrasonic. (A) Doppler type ultrasonic flow measurement. (B) Transit time ultrasonic flow measurement.

particles in the fluid (gas/liquid). Usually the Doppler transmitter sends an ultrasonic beam of frequency around 500 kHz. The frequency shift/difference from the transmitted signal and the receiving signal is measured. The frequency difference is called the beat frequency. The frequency shift is proportional to the velocity of the flowing medium or stream velocity. As seen in Fig. I/3.1.3-4 (middle part) an ultrasonic wave is sent at an incident angle through the pipe wall into the fluid by a transmitter (transducer) external to the pipe. Part of the signal is reflected by suspended particles or bubbles present in the fluid; this signal then travels through the flowing medium in the pipe wall to the receiver. Here the reflectors are traveling at the fluid velocity. So, as per the Doppler principle, there will be a frequency shift of the reflected wave and such a shift is proportional to the velocity of the reflector, i.e., stream velocity. If v is the fluid velocity, f_t and f_r are the frequencies of the transmitting and receiving signals, respectively, then one gets for sound velocity C (for the same medium for transducers):

$$\begin{aligned}\Delta f &= f_t - f_r \\ &= f_t \cdot v \cdot (\cos\theta_t / C) - f_t \cdot v \cdot (-\cos\theta_r / C) \\ &= f_t \cdot v \cdot (\cos\theta_t / C + \cos\theta_r / C)\end{aligned} \quad \text{(I/3.1.3-1)}$$

where θ_t and θ_r are the transmission and receiving angles of the ultrasonic signal. Here, one needs to make the equation free from θ_t and θ_r (i.e., independent of pipe and fluid characteristics) and this can be done by applying *Snell's law* (Subsection 1.2.2.10), which, by using α and β, represent the transmitting beam angle of the transmitter and the receiving beam angle of the receiver decided by the manufacturer [38]. Normally manufacturers set α and β as the same values, i.e., the same angle for both transducers. So, after simplification one gets from Eq. (I/3.1.3-1)

$$\Delta f = 2 v f_t \cdot \cos\alpha / C \quad \text{(I/3.1.3-2)}$$

or

$$\begin{aligned} v &= \Delta f \cdot (C / 2 f_t \cos\alpha) \text{ or} \\ v &= K \cdot \Delta f \quad \text{where constant} \quad \text{(I/3.1.3-3)} \\ K &= C / 2ft \cdot \cos\alpha) \end{aligned}$$

Hence velocity is proportional to frequency shift, which is measured to find v and from there, based on pipe geometry, volume flow is calculated.

- *Transit time type:* In transit time transducers there are two versions as shown in Fig. I/3.1.3-4 (bottom part). One version is where transducers are placed on opposite sides of the pipe and the other version has transducers placed on the same side of the pipe. In the former case the transit times of ultrasonic waves from the transmitter to the receiver both for and against flow are measured to compute fluid velocity. In the second version the transducers are on the same side of the pipe and transit time is measured for the ultrasonic wave to travel across the pipe after being reflected at the pipe and returning to the receiver. As shown in the figure (transducers on opposite sides of the pipe), when the lower transducer (**A**) sends a signal, the time t_{AB} to travel to the upper transducer (**B**) will be given by Eq. (I/3.1.3-4).

  As shown, if v is fluid velocity, L is the acoustic length, θ is the angle of the ultrasonic beam with pipe axis, and C is sound velocity,

$$t_{AB} = L / (C + v\cos\theta) \quad \text{(I/3.1.3-4)}$$

  Similarly, when B sends a signal to A then the time taken is

$$t_{BA} = L / (C - v\cos\theta) \quad \text{(I/3.1.3-5)}$$

$$\text{So, } = t_{BA} - t_{AB}$$
$$= L\{1/(C - v\cos\theta) - 1/(C + v\cos\theta)\} \quad (I/3.1.3\text{-}6)$$

After rearrangement one gets

$$v = (L\Delta t)/2\cos\theta \cdot t_{BA} \cdot t_{AB} \quad (I/3.1.3\text{-}7)$$

If T is the average transit time known from manufacturer then,

$$v = K\Delta t, \left(\text{Where, } K = L/\left(2\cos\theta \cdot T^2\right)\right) \quad (I/3.1.3\text{-}8)$$

So, v can be calculated by measuring Δt.

In the other version of transit time method, the reciprocal of transit time is used to get the fluid velocity. The associated equation is,

$$v = K\Delta f, (\text{Where, } K = L/(2\cos\theta)) \quad (I/3.1.3\text{-}9)$$

After knowing v, volumetric flow can be calculated easily for a known pipe geometry.

- *Cross-correlation type:* A typical such arrangement is shown in the top part of Fig. I/3.1.3-4. The detection method is similar to the transit time discussed with some differences. The difference here is that here transmitters and receivers never swap. On one side there are two transmitters and the other has two receivers. Both upstream and downstream transducers send signals and receive signals, but on account of the eddies and vortices these signals get modulated. This causes two exact wave forms, only these two are shifted in time scale. This time gap is proportional to the transducer and inversely proportional to the fluid velocity. The time difference is calculated by correlation function in a computing device based on signals from two receivers.

5. **Anemometer:** Anemometers are another way of measuring the fluid velocity in a contained flow, such as an HVAC duct or uncontained flow such as air flow in the atmosphere. These are extensively used in HVAC and meteorology. As shown in Fig. I/3.1.3-5, there are three types of anemometers used in industries, as shown in Table I/3.1.3-1.
   - *Cup type:* A typical three-cup anemometer is shown in the top left part of Fig. I/3.1.3-5. These anemometers are insensitive to wind direction, and are used to measure wind velocity. A DC tachometer can be attached to the same to obtain the readouts. The response speed of an anemometer is expressed in terms of the *length of wind* that has to pass through the meter before the velocity sensor response amounts to 63% of a step change in velocity. This is known as the *distance constant* and is generally expressed in units of length (feet/meters) [12].
   - *Vane type:* Vane type anemometers are often used in HVAC as handheld meters. In the vane type design shown in the figure, air flow sets the vane in motion with an angular velocity proportional to the wind speed. These are available as handheld units, or with local indicators. In the case of digital readouts, the vanes have tiny magnet attached to them to create an electrical impulse which is properly conditioned to give a digital readout as shown in Fig. I/3.1.3-5. With the help of magnetic or capacitive coupling it is possible to have remote transmission also.
   - *Impeller type:* This type (not shown) is like turbine blades against a shaft. These are very similar in operation to vane types. They are often fitted with a tachometer to obtain the speed readout.
   - *Thermal/hot wire type:* A thermal anemometer, also known as a hot-wire anemometer as shown in Fig. I/3.1.3-5, is used to measure fluid velocity by monitoring the heat convected away by the fluid, i.e., the hot wire is cooled at a rate that is proportional to the air (or gas) velocity at the probe tip. This intrusive

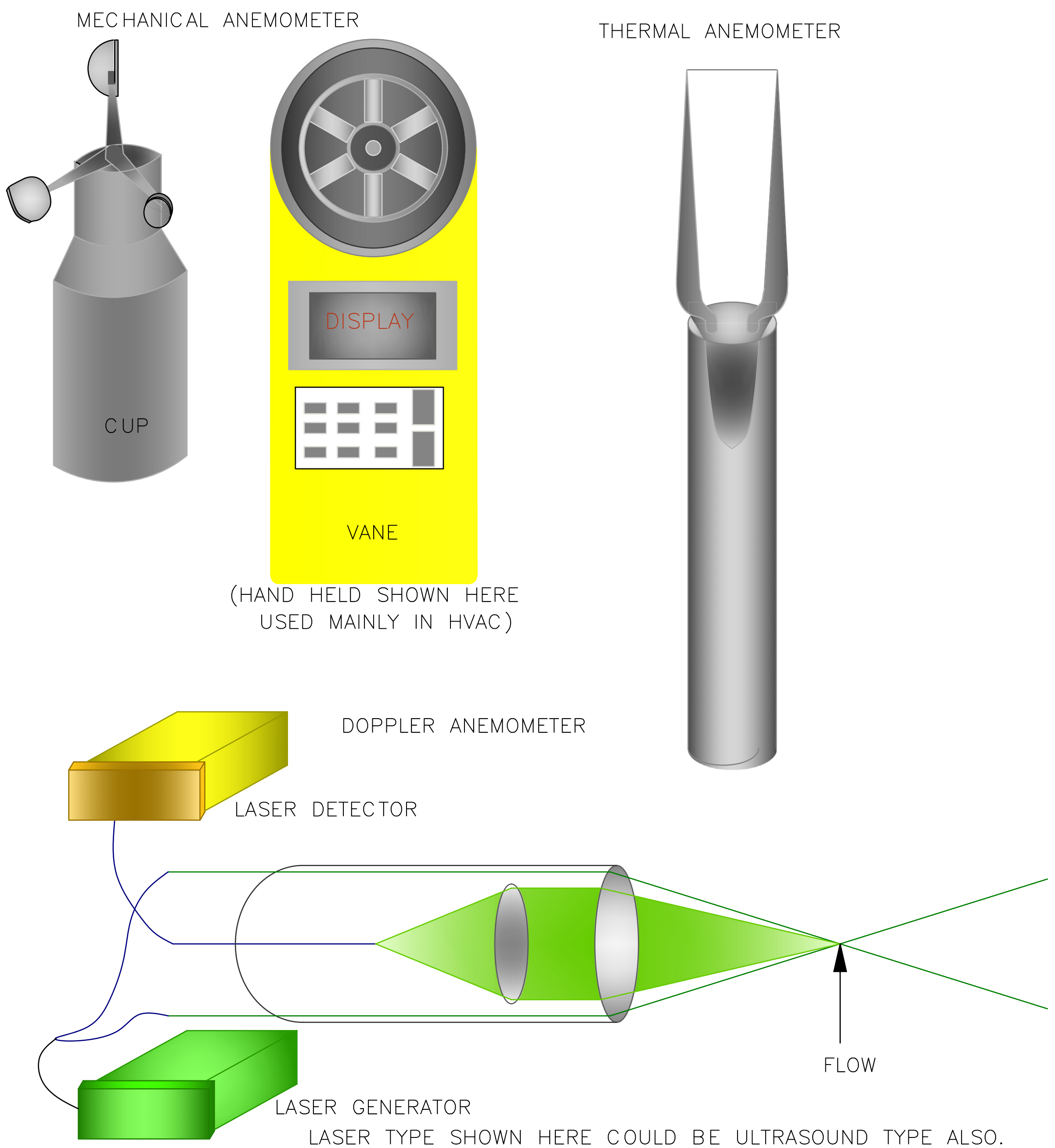


FIGURE I/3.1.3-5 Anemometer.

TABLE I/3.1.3-1 Anemometer Types

	Anemometer Types		
Sub Category	**Mechanical**	**Thermal**	**Doppler**
Category 1	Cup	Constant power	Ultrasonic
Category 2	Vane	Constant temperature	Laser
Category 3	Impeller	Nil	Nil

technique is an ideal tool for measurement of velocity fluctuations in time domain in turbulent flows [39]. These are available in two versions: constant current or constant temperature types. Naturally, in the former case the change in temperature due to fluid is noted to calculate the fluid velocity from a proportionality function. On the other hand, in the second case, a change of current due to fluid flow is noted to calculate the fluid velocity. These are available as single-, dual-, or triple-sensing probes that cover a range of velocities from 0.5−10.0, 0.25−5.0, and 0.1−2.5 m/s, respectively [12].

- *Doppler type:* In Doppler type ultrasonic discussions it has been seen that sound or light is beamed into the atmosphere, and any particles in the air will reflect these beams. These reflected beams may be received in a receiver. In the returning beam frequency there will be a Doppler shift and this can be interpreted as an indication of wind velocity. There are two kinds of Doppler anemometers, i.e., acoustic (ultrasonic) or laser types. The acoustic Doppler devices are more often used than the laser types. In the case of laser Doppler anemometers (LDAs) utilizing the Doppler effect, there will be a Doppler shift of frequency (color), which occurs as light is dispersed from the surface of moving particles. Relative to the frequency of the light, this frequency shift is very small (from 1 kHz up to 0.1 MHz) [12]. Therefore, it is not possible to measure directly and an interference method is utilized. In this method two coherent laser beams are used. When a particle passes through the *intersection* volume formed by the two coherent laser beams, the scattered light, received by a detector, has components from *both beams* hence *interference* occurs at the detector. This interference would produce a pulsating light intensity, as the particle moves. The scattered light fluctuates with a frequency proportional to the velocity of the particle. A typical measuring scheme is shown in Fig. I/3.1.3-5.

  In the case of an ultrasound anemometer there will be two or more pairs of transmitter receiver sets. The transmitter sends a constant signal to the corresponding receiver and electronic circuits inside compute the time taken. Computing circuits measure and calculate the difference in time to find the wind speed. This is similar to transit time discussed in Subsection 3.1.3.4.

6. **Electromagnetic flow meter:** The electromagnetic flow meter uses Faraday's law of electromagnetic induction to measure the process flow. With reference to Subsection 1.2.2.11, it can be seen that, when a magnetic field is placed at right angles to the pipe axis, and an electrically conductive fluid flows in the pipe, an electrode voltage "e" is induced between a pair of electrodes placed mutually at right angles to the direction of the magnetic field and pipe/flow axis. This is depicted in Fig. I/3.1.3-6 (top part concept, bottom part detailed).

   This electrode voltage "e" is directly proportional to the average fluid velocity v. This comes from Faraday's law of electromagnetic induction. Faraday's law states that, when a conductor moves through a magnetic field of a given strength, a voltage is produced in the conductor that is dependent on the relative velocities between the conductor and the field. Also, this induced emf will be at right angles to both vector B and vector v. This induced voltage will be computed by the cross-product (see Subsection 1.2.1.16).

   So when a conductor length is l (or pipe ID D) (m) and is moving with a velocity v (m/s) perpendicular to a magnetic field of flux density B (Tesla), a voltage e will be induced across the ends of the conductor. So, Faraday's law can be mathematically expressed as $e = lBv$. With reference to Fig. I/3.1.3-6 (top part—conceptual part), l can be replaced by the pipe internal diameter (ID) D so,

$$e = DBv \text{ or } v = e/DB \qquad \text{(I/3.1.3-10)}$$

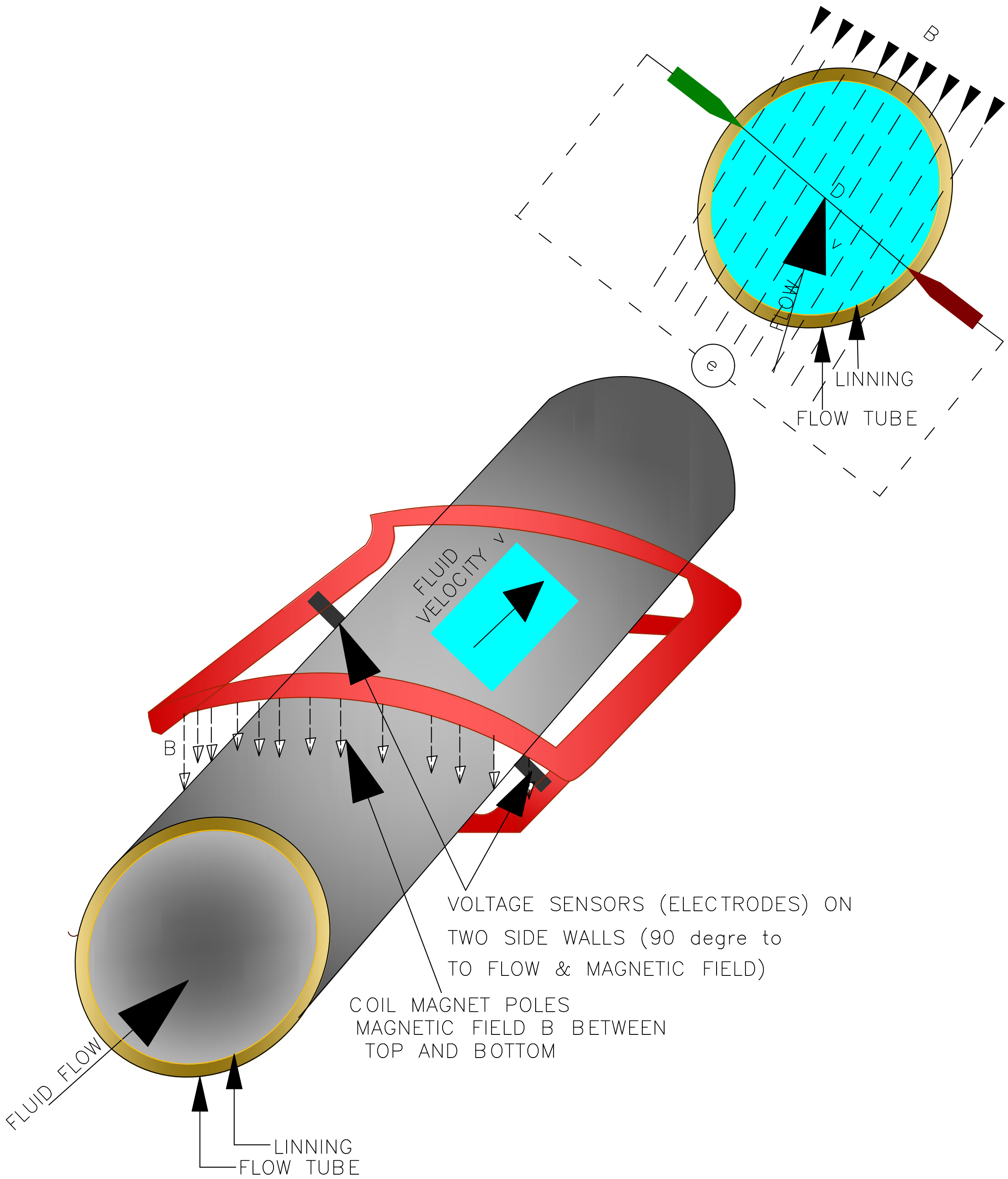


FIGURE I/3.1.3-6 Electromagnetic.

$$\text{Again volume flow } q_v = \pi\left(D^2/4\right)\cdot v \text{ or } q_v = \pi(D/4B)\cdot e \text{ or, } q_v = K\cdot e \quad \text{(I/3.1.3-11)}$$

Therefore, for a given pipe geometry and magnetic field, D/B is constant and volume flow is proportional to induced voltage "e."

As performance depends on the magnetic field, it is important that the pipe (the metering tube) should not have any influence on the magnetic field. In order to prevent short-circuiting of the magnetic field, the pipe (metering tube) must be manufactured from a nonferromagnetic material such as stainless steel or nickel-chromium [5]. Induced voltage "e" is measured by means of two metallic

electrodes, in electrical contact with the measuring medium. Accordingly, based on the flowing medium, a suitable metallic material should be chosen so as to provide resistance to chemical corrosion, abrasion, pressure, and temperature. Commonly used materials include 316 stainless steel, HastelloyC, Monel, etc. It is also important to ensure that the two sensing electrodes are not electrically short-circuited through the tube wall. For this reason, the metering tube is lined with an insulating material such as Teflon, PTFE, neoprene, ebonite, etc. Another important issue is that for operation of an electromagnetic flow meter, there is a requirement for the minimum conductivity of a fluid. This is again dependent on the excitement type and meter size. For an AC field excitement it is 0.05−20 μS/cm and for DC field excitement it is 1−20 μS/cm.

The liquid in a pipe cross-section can be conceived of as an infinite number of conductors moving through the magnetic field, naturally, each element will have a contribution to the voltage generated, meaning that there are a number of individual "generators" contributing to the instantaneously generated voltage. Therefore, the signal voltage generated can be considered proportional to the average velocity, almost regardless of the flow profiles. In electromagnetic flow meters it is possible to measure both forward as well as reverse flow. These flow meters are generally independent of the influence of fluid viscosity, density, etc. and are capable of a fast response to changes in flow. These flow meters are available in various types and sizes for different applications. However, they need detailed and complex considerations for design. These are discussed at length later.

7. **Target flow meter:** When considered with the other flow meters in this subsection, the target flow meter is the odd man out as flow measurement in this meter is based on applied force on the target, which is directly located in the flow path. Target flow meters are often called drag-body target/drag-force flow meters because the drag force on the inserted meter is measured in terms of flow velocity. The targets are normally a flat disc or sphere. Targets are inserted into the flow path with the help of an extension rod as shown in Fig. I/3.1.3-7. There are two main detection methods, namely, force measurement by strain gage or deflection method.

The former method is most often used. However, there are instruments where the deflection force bar is attached to the target, due to the moving fluid being measured/detected by the reluctance device. In such a case, the deflection is dependent on the target area, fluid density, and fluid velocity. In this method, the flow rate is measured by measuring the force exerted on the target. Of the various ways and means of force measurement, the force is mostly sensed by a strain gage, i.e., a strain gage detects the impact forces produced by the flowing fluid. The standard design the meter is also available as a retractable type. The flow meter allows unimpeded flow of condensates and extraneous material along the bottom of the pipe while allowing unimpeded flow of gas or vapor along the top of the pipe [12]. Targets are available in various shapes and sizes and are capable of covering a large range of Reynolds numbers. The force on the drag−body target can be expressed as per the following equation for a target of area A_t, flowing fluid velocity and density as v and ρ, respectively.

$$\text{Drag Force } F = C_d \cdot \rho \cdot v^2 \cdot A/2$$

$$(C_d \text{ stands for overall drag coefficient}) \quad \text{(I/3.1.3-12)}$$

The drag coefficient is empirically obtained and for different target shapes it varies, such as: for a sphere-shaped target it is 0.07−0.5 and for a flat target it is 1.28 (typical). These are available in a wide range of flows. However, as this is mainly a proprietary device, test data

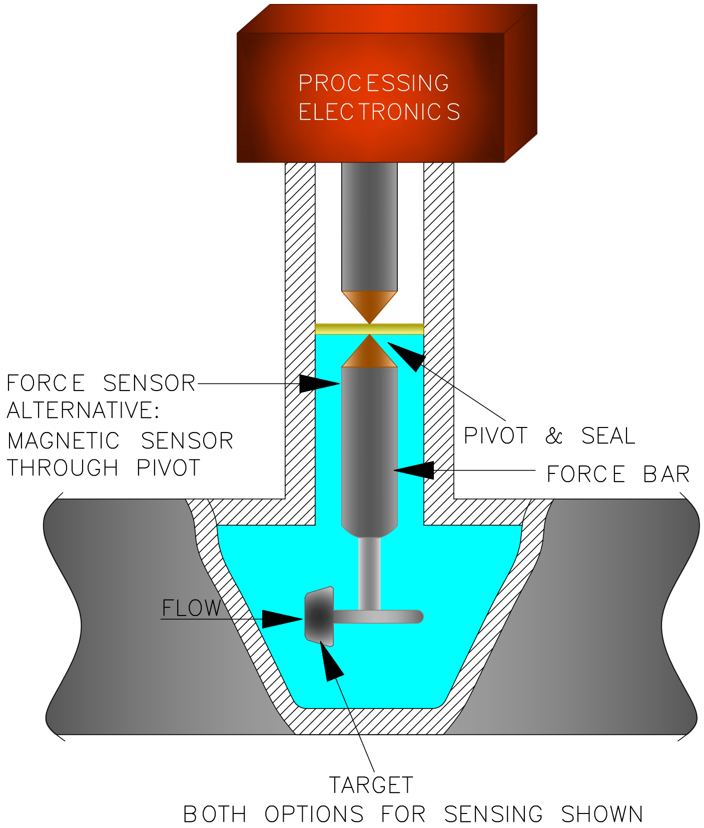


FIGURE I/3.1.3-7 Target.

According to Encyclopedia Britannica Fluidics is the technology of using flow characteristics of fluid to operate a control system. In fact fluidics technology provides sensing, computing and controlling functions with fluid power through interaction of fluid. The technology was there but only after 1959 this has been utilized in commercial way. It originally was represented as fluid amplification. Coanda effect and momentum exchange flow meters utilize fluidics.

FIGURE I/3.1.3-8 Fluidics.

are not easily available and the manufacturer provides the calibration data [12]. Its accuracy and repeatability are quite good. One of the major advantages of the target meter includes the ability to cope with highly viscous fluids at high temperatures [5]. Its use in heavy oil flow measurement in boiler applications is quite popular. The absence of any moving parts and easily changed range and fluid by changing the target and readjusting the meter are major advantages of this meter over other meters. Therefore, it can be used for a wide range of fluid types. High head loss is one of its major disadvantages.

With this the discussions on volumetric flow measurements are concluded and we now see how mass flow can be measured directly.

3.1.4 MASS FLOW METER TYPES AND PRINCIPLES

There are basically two categories of mass flow measurement: mechanical means and thermal means. In this section both principles will be discussed.

- *Mechanical mass flow measurement:* For mass flow measurement in process and other industrial plants, a Coriolis flow meter based on Coriolis force is the most popular. However, prior to discussing this, we recap the basic physics so as to understand how the general properties of matter can be exploited to measure mass flow. Mass flow measurements are always preferred for material balance, cost, etc., because mass is an intrinsic property and is independent of density, which in turn varies with pressure, temperature, etc. The discussions on mass flow measurement start with Newton's second law of motion as it is known that force is equal to mass multiplied by acceleration, i.e., the rate of change in momentum, meaning force $F = m \cdot a$, where m = material mass and a = acceleration. This is true for linear motion. When this is applied to angular motion one gets

$$\text{Torque } \tau = I \cdot \alpha \qquad \text{(I/3.1.4-1)}$$

where, I = moment of inertia, m = mass of the material; and α = angular acceleration.

So,

$$\alpha = \omega/t$$

where ω represents angular velocity; t = time, and I of mass m is given by

$$I = m \cdot r^2;$$

where r = radius of gyration.

Therefore, from Eq. I/3.1.4-1,

$$\tau = I \cdot \alpha = m \cdot r^2 \cdot \omega/t \qquad \text{(I/3.1.4-2)}$$

Thus, one gets the mass flow rate as

$$m/t = \tau/\left(r^2 \cdot \omega\right) \text{ or } mg/t = \tau g/\left(r^2 \cdot \omega\right); \text{ to obtain dimension of force} \qquad \text{(I/3.1.4-3)}$$

Again, for a linear system it is known that the momentum of material with mass m and velocity v is: momentum $= mv$. Similarly, for an angular system, *angular momentum* H is given by

$$H = I\omega \text{ or } H/t = I \cdot \omega/t = m \cdot r^2 \cdot \omega/t; \text{ so, one gets, } H/t = m/t \cdot \left(r^2 \cdot \omega\right) \qquad \text{(I/3.1.4-4)}$$

Since the radius of gyration for any system is constant, when angular momentum is introduced into the system, then mass flow can be measured by measuring torque developed [12]. So, from the above explanations, we understand the various possibilities for mass flow measurements.

Coriolis' effect may be understood from Fig. I/1.2.2-8. Let there be a disc with radius R rotating with angular speed ω. Now, if there is a point "A" located on the disc at "d" from center ($d < R$) one mass m is located. If the mass at "A" is to be moved radially to another point B (at R from center) some additional force and energy will be required. This is due to the inertial force, known as the Coriolis effect [1].

$$\overline{F_c} = -2m(\overline{\omega} X \overline{v})$$

where v is the velocity at which mass is moved from A to B, in a direction perpendicular to both vectors (radial and tangential)

$$F_c = -2m\omega v \qquad \text{(I/3.1.4-5)}$$

Here it is seen very clearly that the product of m and v stands to give the mass flow and ω is the rotational vector. In mass flow measurement utilizing Coriolis effect the flow of fluid is passed through a set of tubes which are set to vibrate. On account of the Coriolis effect these pipes will be twisted. This is further explained in Subsection 3.1.4.1. There are a number of flow meters developed based on these principles: impeller turbine flow meters (where the impeller is run by a synchronous motor through a magnetic coupling to impart

TABLE I/3.1.4-1 Symbols and Units for Mass Flow Metering

Symbol	Parameter	Unit	Symbol	Parameter	Unit
F_c	Coriolis force	kg·F	d, R	Distance	m
τ	Torque	kg·m	H H	Angular momentum Heat (thermal mass flow)	kg·m·s cal
ω	Angular velocity	rad/s	α	Angular acceleration	rad/s^2
r	Radius of gyration	m	m	mass	kg
t	Time	s	v	Linear velocity	m/s

angular velocity to the fluid), gyroscopic mass flow meters (based on gyroscopes), twin turbine mass flow meters, and Coriolis mass flow meters. In subsequent sections the latter two types will be discussed. Various symbols and units used are summarized in Table I/3.1.4-1.

- *Thermal mass flow measurement:* One can recall theory of calorimetry that heat transfer between two media, heat gain = heat loss, and in each case of heat gain or heat loss the amount of heat transfer H is related to the mass m and temperature difference ΔT between two media by the following relation:

  $H = m \cdot C_p \cdot \Delta T$ (where C_p is the specific heat cal/kg°C), so dividing both sides by t

$$H/t(\text{cal/h}) = q_m \cdot C_p \cdot (T_2 - T_1) = q_m \cdot C_p \cdot \Delta T \quad \text{(I/3.1.4-6)}$$

where $q_m = m/t$ (kg/h), T_1 and T_2 are the initial and final temperatures before and after heat transfer, respectively.

Thus,

$$q_m = H/t\{C_p \cdot (T_2 - T_1)\} \quad \text{(I/3.1.4-7)}$$

Now if heat transfer H is maintained by a heater with constant current, i.e., from electric *power* heat quantity per unit time (H/t) is known. When the heater is immersed in a fluid of known C_p then, by measuring ΔT with the help of temperature elements (T/C, RTD), one can compute the mass flow rate. It is time to look at things in slightly more detail.

1. **Coriolis flow meter:** As stated earlier, in Coriolis flow meters the liquid is passed through a set of tubes. In order to minimize the energy requirement, these may be set to vibrate at a natural frequency. One thing to be remembered is that instead of two tubes, a single tube will give the same result, however for higher sensitivity and to facilitate measurement two tubes are used. When one concentrates on Eq. (I/3.1.4-5) one sees that there is a mass flow (mv) with one rotational vector ω.

   As can be seen in Fig. I/3.1.4-1 (two sets shown but for understanding ***one*** will do), the flow from the main flow tube enters into U tube and after passing the U tube, it returns to the main flow tube. The tube(s) is vibrating, i.e., the free end vibrates. When there is no flow (mv = 0), the Coriolis force is zero. When fluid begins to flow, the Coriolis force comes into action. On account of the Coriolis force, when mass flow begins it will try to oppose the vibration. Now, as the directions of flow at the inlet and outlet are opposite, the Coriolis effect will be opposite, i.e., at the inlet section, the Coriolis force tends to decelerate the movement of the oscillating tube shown in Fig. I/3.1.4-1, whereas, for the outlet section, the Coriolis force tends to accelerate the movement. Obviously there will be a point in the middle where the Coriolis force is always zero, since either is zero for *straight tubes* or is *parallel* for curved tubes, bringing the product to zero [12]. Therefore, on account of the opposite directions of the Coriolis effect,

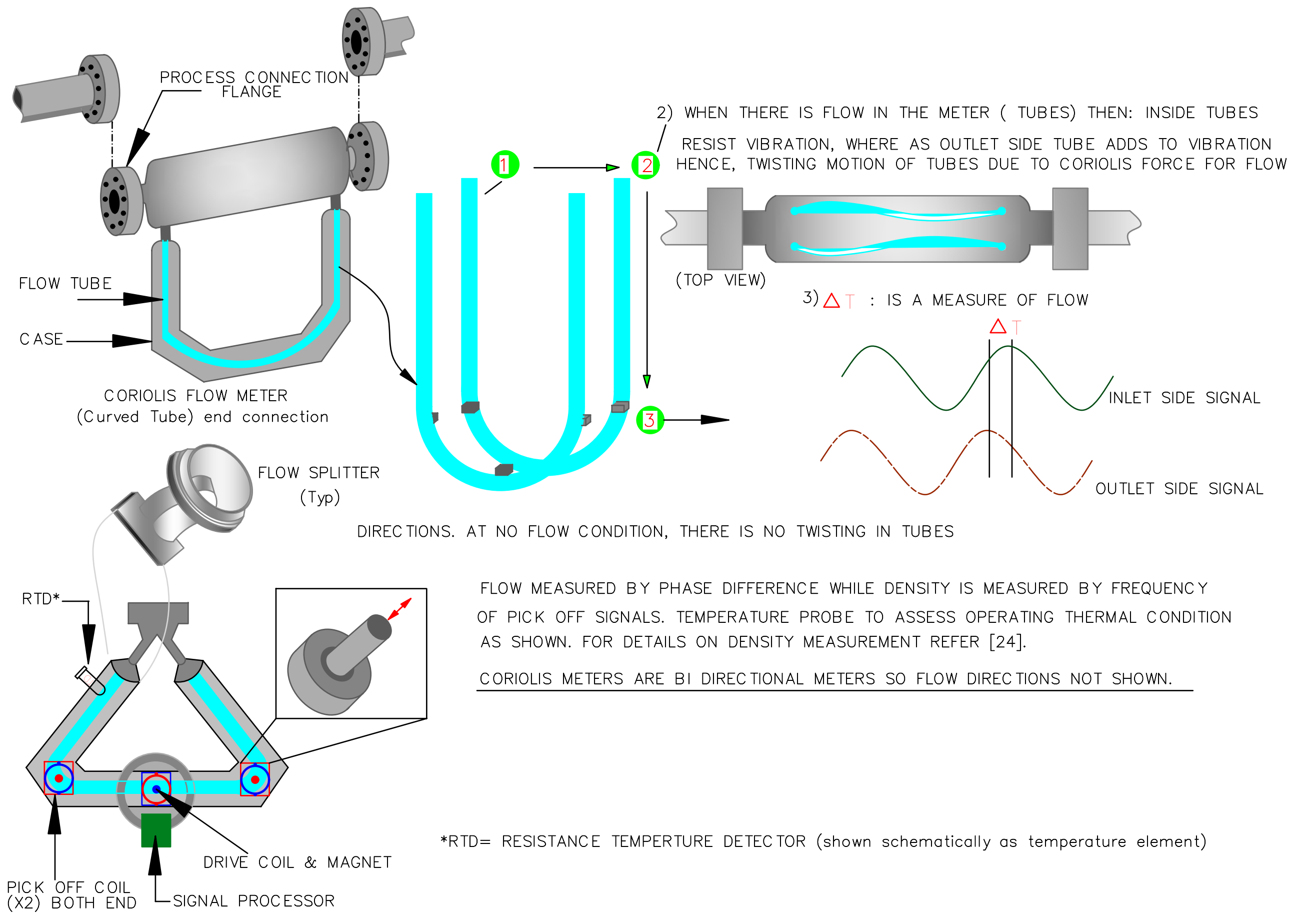


FIGURE I/3.1.4-1 Coriolis mass. *Figures have been developed based on a micromotion tutorial on curved tube Coriolis flow and adapted from my book S. Basu, A.K. Debnath, Power Plant Instrumentation and Control Handbook, Elsevier, November 2014, http://store.elsevier.com/Power-Plant-Instrumentation-and-Control-Handbook/Swapan-Basu/isbn-9780128011737/ courtesy of Micromotion and Elsevier.*

there will be a twist in the tube(s) as shown in the right-hand side of Fig. I/3.1.4-1. This will introduce a phase shift along ***the tube***. This phase shift is proportional to the mass flow. This phase shift means there will be difference in time in occurrence of the peak in the vibrating curve as shown in the figure. So, the mass flow can then be determined by measuring Δt (the phase shift) by pick off as shown in the figure. As stated earlier, single tube will do, but twin tubes are used to improve sensitivity. As shown in Fig. I/3.1.4-1, for twin-tubes, two motion sensors at both sides are needed to measure the twist in the tubes. The sensor could be of any type to represent the motion of the flow tubes, measuring position, velocity, or acceleration. In the majority of cases (e.g., a Coriolis meter of micromotion) the time lag between the two sets of sensors is measured with the help of electromagnetic pick off to get the mass flow. Another good side of the meter is that it can help in determining the density (which is beyond the scope of this book). As the oscillation is at the natural frequency of the system, if the ***density*** (another measuring parameter in this meter) of the fluid in the tube is changed, then the frequency of the vibration will also change.

2. **Twin turbine:** As stated earlier, there is another kind of mass flow meter where angular momentum could also be exploited for measurement of mass. This twin turbine mass flow measurement has been detailed in Fig. I/3.1.4-2.

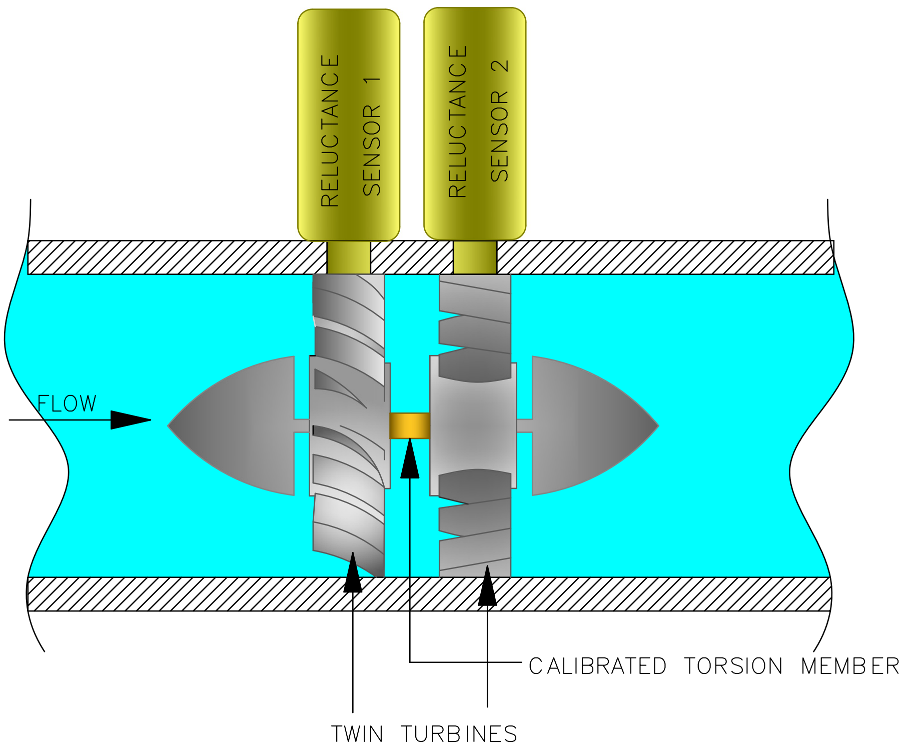


FIGURE I/3.1.4-2 Twin turbine.

In this instrument, there are two turbines mounted on a common shaft as shown in Fig. I/3.1.4-2. There is a calibrated torsion member to couple them. Each turbine is designed with a different blade angle and a strong magnet is located in each turbine in a twin–turbine assembly. So, on account of the different angle, they would have a tendency to turn at different angular velocities. However, on account of the torsion member in between, such motion is restricted and the entire assembly rotates in unison at *some* average velocity [12]. Also, the torsion member that holds them together is twisted. On account of the varying blade angle there will be an angular phase shift that develops between the two turbines. This angle is a direct function of the angular momentum of the fluid [12]. From earlier discussions it has been established that angular momentum can be measured by torque, and angular momentum is a function of mass flow. As discussed above the torsion member is twisted, and the angle developed between the two turbines is a direct function of the twist or torque exerted by the system. A reluctance-type pickup coil is mounted over each turbine and this in conjunction with the strong magnet at the turbine measures rather than computes the angle of twist. As each turbine magnet passes its own pickup coil, the coil generates a pulse. Thus, out of the two pulses generated one may be used to open a logic gate and the other could be used to close the logic gate. An oscillator is in the electronic circuit and this is driven by the logic gate pulses. Therefore, the number of oscillations becomes a function of the angle between the two turbines, which is a function of torque, and hence is proportional to the mass flow rate (Eq. I/3.1.4-3).

3. **Thermal mass flow:** There are various kinds of thermal flow meter utilizing the same principle but implemented in different ways as detailed in Fig. I/3.1.4-3.

With reference to Fig. I/3.1.4-3, it can be seen that there is a classification of thermal

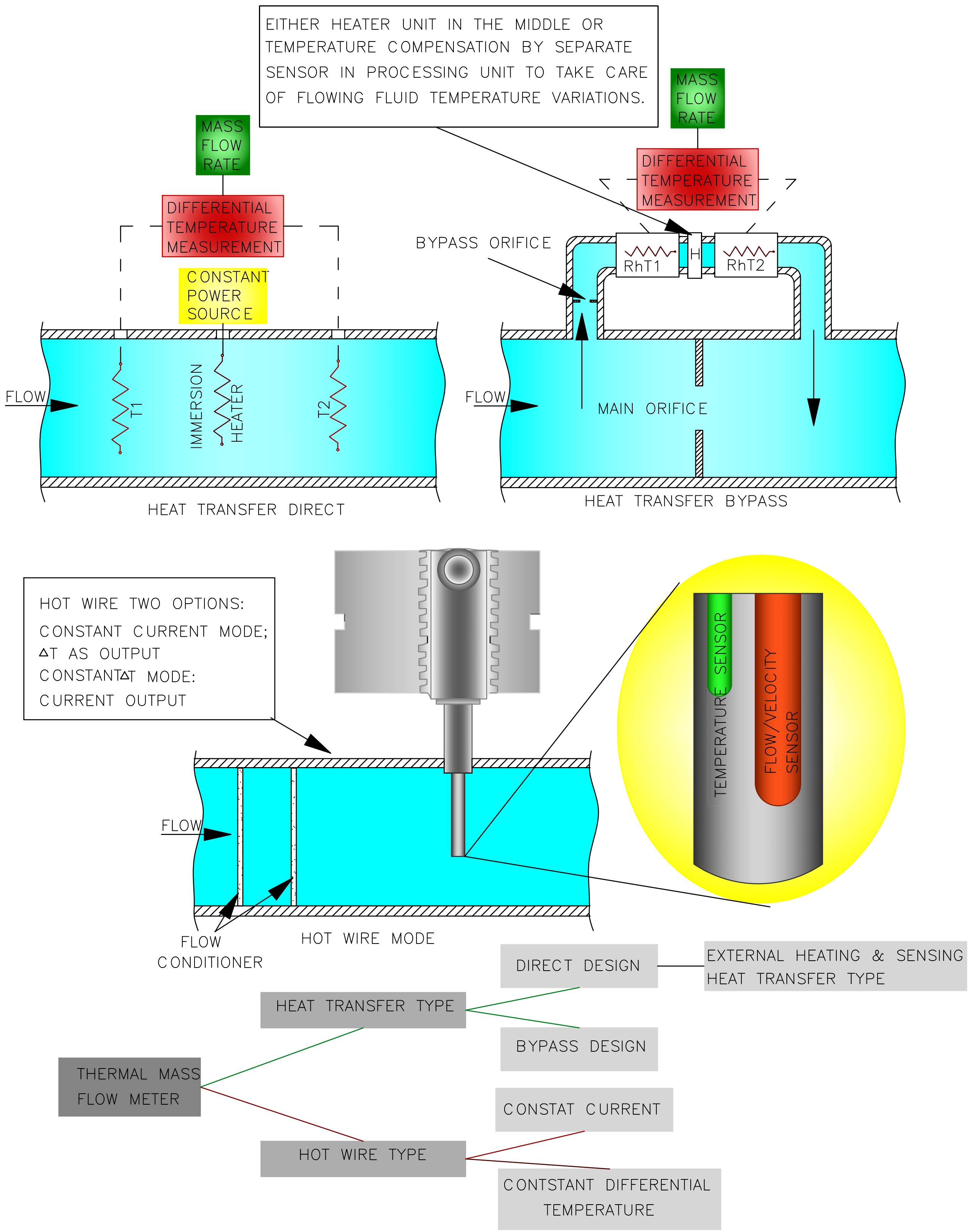


FIGURE I/3.1.4-3 Thermal mass. *Based on an idea from Process Design Practices Flow Meters and Orifices; CK, December 2009, http://www.korf.co.uk/PDP%2006-FO-P5_P14.pdf. Courtesy: Omega Engineering USA.*

mass flow meters, these are the heat transfer method and hot wire type. The discussion starts with the heat transfer method.

- *Heat transfer method:* There are some variations in mass flow measurements in the heat transfer method, as described here.

  Heat transfer method in main line: As can be seen in the top part of Fig. I/3.1.4-3, it consists of three major elements. One is the heater in the middle where the immersion heater is heated by electricity. The power supplied to the heater is equal to the heat transferred to the fluid. Therefore, heating power is monitored by a wattmeter to get proportional heat transferred to the fluid. There are two temperature-monitoring points (upstream and downstream of the heater) to measure the temperature difference that is created. For a given fluid C_p is known, therefore mass flow can be computed utilizing (Eq. I/3.1.4-7). In this case the heater is placed in the main flow path. This method has some limitations, such as being applicable mainly for low-flow applications and as temperature sensors are exposed to fluid these are subject to erosion and corrosion (though with proper selection of thermowell such problems can be circumvented). However, these three elements in any case cause additional restriction to process flow! And also there could be a fair chance of system leakage. There is another version to cater to high-flow systems.

  Bypass heat transfer method: Bypass thermal mass flow meters may be comprised of a capillary sensor tube used as a shunt to the main flow line. However, in practical applications a bypass line may be constructed as has been shown in the top-right part of Fig. I/3.1.4-3. These are used mainly in low-flow (laminar) measurements. For large-flow applications however there is a necessity for a main and a bypass orifice so that a known part of the fluid is bypassed. Here combinations of orifices are designed, for a known percentage bypass of the main flow (i.e., the fraction of main flow bypass is known). In bypass line heat transfer type sensing as discussed above is deployed to know the mass flow in the bypass line. As a fraction of total flow in the bypass line is known, total mass flow can be computed. With the help of a bypass system the issue of low-flow conditions can be combated, but other issues such as chances of leakage, erosion, corrosion of temperature elements, etc. are not totally eliminated. Therefore, external heater sensor methods are used.

  External heating and sensing method: When a fluid flows in a pipe (turbulent or laminar), a thin layer (film) exists between the main body of the fluid and the pipe wall. If the heater is sufficiently insulated, and if the piping material is a good heat conductor [12], the heat transfer from the heater to the fluid can be expressed as

$$H = h \cdot A \cdot (T_{wall} - T_{fluid}) \qquad \text{(I/3.1.4-8)}$$

where h stands for heat transfer coefficient, A = area of pipe through which heat transfer takes place, and T_{wall} and T_{fluid} are the temperature of the wall and fluid, respectively. From a standard treatise of fluid mechanics and thermodynamics it can be seen that h varies with q_m mass flow and finally one can arrive at

$$q_m^{0.8} = C/(T_{wall} - T_{fluid}) \qquad \text{(I/3.1.4-9)}$$

where C stands for a constant comprising fluid properties, e.g., absolute viscosity (μ), thermal conductivity of fluid (K), specific heat of fluid (C_p), and meter design parameter: heat supplied, (H), pipe diameter (D), and area of pipe for heat transfer (A). For a particular fluid and pipe geometry these are constant, so that ΔT can give mass flow and the relation is nonlinear. The downstream temperature sensor is located near the heater so that it measures T_{wall}. The upstream temperature sensor is located where the wall and fluid temperatures are in equilibrium [12].

- *Heat loss/hot wire method:* This method uses the flow rate-dependent heat transfer from a heated body to the measuring medium [1]. A hot body (a heated wire) is placed in the main stream of the flow as shown in Fig. I/3.1.4-3 (middle part). The reader's attention is drawn to the blow up of a sensor that is shown. Here it is to be noted that there are two sensors, namely, a flow or velocity sensor and a temperature sensor. As the name implies, the first is the hot wire to sense the flow. The other sensor is to sense the temperature of the flowing fluid for temperature compensation given in the circuit.

  Here the hot wire is heated by an electrical power source in I^2R, where I is the current in the circuit and R is the resistance of the hot wire. On account of process flow some part of this heat energy will be taken away by the fluid. This is because of the fact that the molecules (mass) of the flowing fluid would interact with the heated surface of the sensor and would take away the heat, which is a function of the power (current) of the heating circuit. The higher the flow rate (velocity), the more heat will be taken away. This is fine if the temperature of the flowing medium can be kept at a constant temperature. There are two types, in one type ΔT between the flow sensor and temperature sensor is kept constant and the circuit current gives the output; the other option can keep current in the flow sensor heating constant and the difference in temperature would be the output for flow. Most often the former example is used. An electrical circuit applies heat to the resistor so that a constant temperature difference exists between the resistors. The power P is, thus, a measure of the gas mass flow rate. With K1…3 being the instrument and fluid s dependent constants [1] the output power can be derived from King's equation:

$$P = \Delta TK1 + K2(q_m)^{K3} \qquad (I/3.1.4\text{-}10)$$

  In connection with this hotwire anemometer discussions may be referred to. Since the thermal mass flow sensor is an insertion type sensor, in line with the Pitot sensor it has one disadvantage, which is that if the insertion is made at a place where the velocity profile is not representative then there may be error in measurement. Therefore, care needs to be taken.

  The discussions on mass flow and closed pipe fluid flow are concluded and we now explore fluid flow measurement in an open channel.

3.1.5 FLUID FLOW MEASUREMENT IN AN OPEN CHANNEL

So far we have concentrated was on fluid flow measurement in closed pipes. However, in our surroundings there are flows in open surfaces also, e.g., flow in a river. How do we measure this? Even in industrial applications there are cases where open-channel flow measurements are necessary, e.g., the intake of raw water flow to a pretreatment plant. Normally open-channel flow refers to the flow in any channel in which the liquid flows with a free surface [40]. In certain cases, like sewerage, the flow is in a closed channel but it is considered to be under an open channel because the flow is partially filled and not pressurized. Sewer systems, sewage treatment plants, plant intake/raw water systems, industrial waste applications, and irrigation systems all fall under open-channel applications. Hydraulic structures are the most common methods of measurement of open channels. A calibrated restriction inserted into the channel controls the shape and velocity of the flow [40]. Such restricting devices are referred to as primary measuring devices for open-channel flow measurement. Normally such primary measuring devices fall under one of the two categories of flumes and weirs. Unlike closed pipes, in open channels the flow rate is determined by measuring the change in liquid level in or near the restriction.

A *flume* is a specially shaped static structure that is used to restrict the free surface flow in such

a way as to establish relationship between the liquid level and flow rate. Flumes are open channels used as a flow section. Flumes provide some restriction in the channel area and/or a change in channel slope. As stated above, the flow rate in the channel is determined by measuring the liquid depth at a specified point in the flume. A *Parshall flume* is the most common type flume but there are other types, e.g., Palmer–Bowlus flumes [40].

A *weir* is an obstruction built across an open channel over which the liquid flows, often through an opening which has been designed in a special shape. There are three types of weir: *triangular* (*V-notch*), *rectangular*, and *trapezoidal* (*Cipolletti*) weirs.

In channel hydraulics "***the Froude number***" is a very important parameter, especially where the weight of liquid is an important force (force of gravity) like that in an open-channel flow measurement. It is a dimensionless number that expresses the ratio of inertial force on an element of fluid to the weight of the fluid element.

$$F_r = v/\sqrt{\mathbf{gl}} \text{ or } F_r = v/\sqrt{\mathbf{gh}} \qquad \text{(I/3.1.5-1)}$$

where v is the velocity of fluid, and l is the characteristic length, often it is the water height h from the floor of the channel (especially for a rectangular channel). For fluid velocity when $F_r < 1$ it is referred to as a subcritical flow regime. "At wave propagation velocity the value of Fr is 1. In the wave propagation velocity condition a standing wave occurs which cannot move, neither upstream nor downstream" [1]. For fluid velocity, when $F_r > 1$, it is referred to as a supercritical flow regime. A short description of F_r is given here—for further details Chapter III may be referred to.

There are several standards to cover the design of these primary devices, some of the major standards include but are not limited to ISO 3847 (SIS6330), ISO 9826 for Parshall flume calculations, ISO 1438 for weirs (also Parshall flumes). To have a close look at these flumes and weirs, the discussion starts with flumes and then weirs. During the discussions primary devices mainly used in instrumentation in industries have been included, and this covers all the major types.

1. **Flumes:** Flumes normally have three sections: a converging section for fluid acceleration (at the entrance $F_r < 1$), passed on to the parallel throat where it goes to a critical or supercritical regime ($F_r > 1$), and at discharge liquid slows down for transition to downstream. Depending on the design there are variations in dimensions. Flumes can be broadly classified as short-throated (e.g., Parshall, Montana, USGS, trapezoidal cutthroat) and long-throated flumes (e.g., Palmer–Bowlus, RBC) [41].
   - *Parshall flume:* To initiate the discussion, refer to Fig. I/3.1.5-1. This flume is named after R.L. Parshall, who worked for the US Agriculture Department.

     This device is a special type of Venturi flume without a dam (present in weirs), and it has much less of a reaction with flowing fluid [1], hence velocity effects are practically eliminated and so there is no need for an upstream stilling chamber. The approximate loss of head is nearly a quarter of that for a weir of the same capacity [12]. Like a Venturi tube, on account of the construction, there will be some energy conversions due to flow in a Parshall flume. Naturally, fluid in the constriction region will accelerate. In addition to constrictions at the sides, there could be some constrictions with elevated floor sections also. In a Parshall flume there are subcritical (see Chapter III) flow regimes, i.e., mainly due to gravity, as well as supercritical (see Chapter III), i.e., higher flow (discussed earlier). At the flume inlet, the water is quiet, because it is dammed, and the flow velocity is in subcritical flow conditions. On account of the acceleration of water in the constricted region, the water enters a supercritical regime. So, downstream level has very little effect on the measurement as long as the level near the downstream end of the

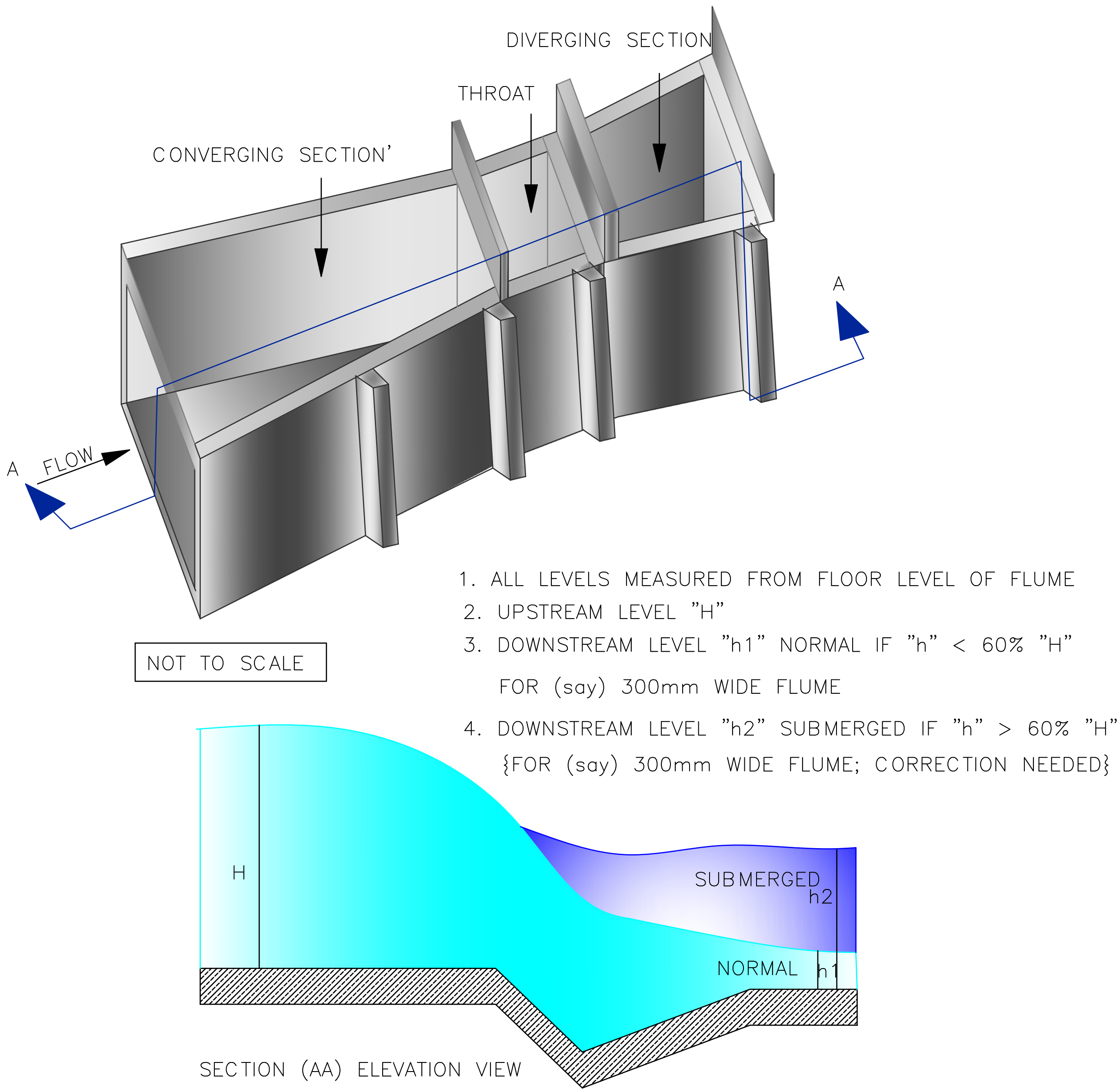


FIGURE I/3.1.5-1 Parshall flume.

throat is <70% of the level near the upstream end. This condition ensures a unique relationship exists between the level of the headwater and the flow rate. When, due to operating conditions, the level at the throat is >70% of the upstream level, it is referred to as *submersion* condition. In submersion conditions, flow measurement requires a correction factor based on both the upstream and downstream levels in flow computation, maintenance of accuracy, and special equipment is usually required for direct readout of flow [12]. After the channel, there will again be a subcritical flow regime. After the channel expansion there will be a hydraulic jump (see Chapter III) and a standing wave [1]. The major advantages of this device include the following.

- High flow rate;
- Low loss;

- No sharp edge or pocket;
- Local fabrication possible;
- No built up on dam (absent);
- Rangeability 35:1 in a single unit [12];
- Higher accuracy and repeatability;
- Better stability and dependability.

  However, it is costly and carrying over of silt, deposits due to higher velocity (at constriction), and depositing in downstream may affect level measurement and so affect accuracy in measurement. Also, the change of elevation of the floor of the flume makes it difficult to install a Parshall flume in an existing channel.

For free flow and for known throat width b, volume flow q_v is given by:

$$q_v = Ch^n (\text{where C and n are given for constriction widths}) \quad \text{(I/3.1.5-2)}$$

The basic formula for calculating flow in a rectangular Parshall flume from the level is given by:

$$q_v = \frac{2}{3} \cdot \mu \cdot b \cdot \sqrt{2g} \cdot (h)^{3/2} \quad \text{(I/3.1.5-3)}$$

where h = level/head, b = throat width. From Eq. I/3.1.5-2, it is clear that there are variations in the flow-measuring formula with throat width. Both ISO9826 (in SI units) and ASTM D1941(English units) provide the calculations for various throat widths. Also, ISO9826 and IS14371 provide dimensional details and constructional details of Parshall flumes for various throat widths “b,” which in standard cases varies from 0.25 to 2.4 m. For different b, values of other dimensions of throat, entrance section, and exit sections are given in tabular form, which may be referred to by the reader to design a system. All the dimensions must be strictly followed so that standard discharge tables can be used. Also, the drop in the floor of the flume should be noted, as it can make it difficult to install a Parshall flume in an existing channel. There are also guidelines in the standard for placing the measuring level, typically the flow rate through a Parshall flume is measured by measuring the liquid level one-third of the way into the converging section.

- *Other flumes:* Amongst the other flume types, the Palmer–Bowlus flume, Khafagi flume, parabolic flume, etc. find their applications. On account of their rounded bottoms and relatively small size, Palmer–Bowlus flumes are easier to install in pipe inverts, ends, and sewer manholes. They are designed to be installed in an existing channel with minimal effort. Palmer–Bowlus flumes provide smaller head change for flow. Here flow is determined by measuring the liquid level at a point half of the pipe diameter D, as shown in Fig. I/3.1.5-2A in the upstream side from the flume throat. All dimensions are scalable and mainly with respect to pipe inner diameter D. This makes it possible to have various sizes. Because of the raised throat, there is the possibility for silt deposits. A Palmer–Bowlus flume with a trapezoidal throat with a flat bottom has emerged as the standard design for circular pipes [40]. There are other flumes, such as Khafagi flume, which is similar to the Parshall flume but does not have a proper parallel throat, as shown in Fig. I/3.1.5-2B.

2. **Weir:** A weir is a dam mounted at right angles to the direction of flow, over which the liquid flows. For measurement of flow, it is used to ensure a free flow stream that is completely ventilated. Ventilation means free access of air under the overflow to ensure that the stream will separate and fall freely. The stream of water leaving the crest, referred to as the *nappe*, should have sufficient fall for accurate flow measurement. Dams constructed from metal with sharp metering edges are normally classified as triangular (or V-notch with the notch

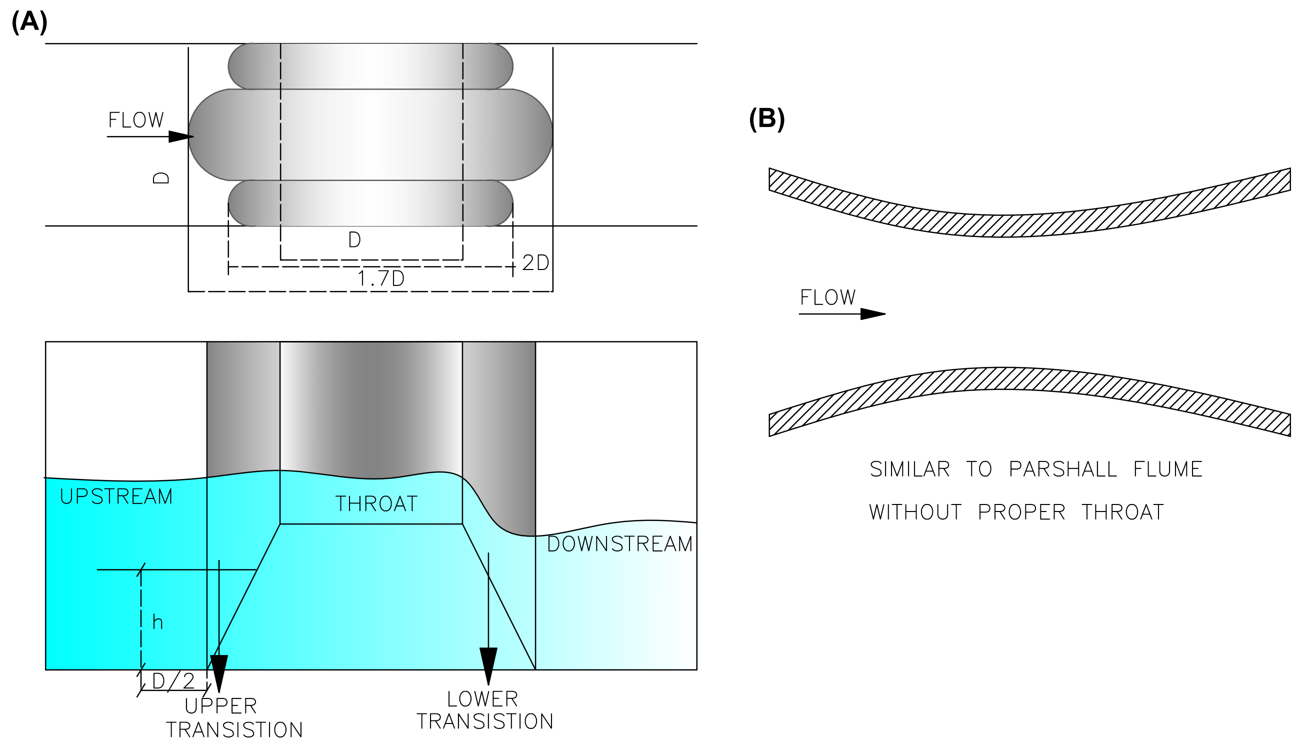


FIGURE I/3.1.5-2 Other flumes. (A) Palmer−Bowlus flume. (B) Khafaji flume. *Drawn after adaption from B. Dawson, Open Channel Flowmeters, Isco Inc, Reprint From: Measurements & Control Magazine, http://www.isco.com/WebProductFiles/Applications/202/Papers_and_Article_Reprints/OpenChannelFlowMeters_Article.pdf.*

angle varying between 30 and 90 degrees depending on flow capacity), rectangular and trapezoidal (or Cipolletti) weirs. The upstream edge of the weir is sharp and straight, whereas the downstream edge is beveled at about 45 degrees (0.8-mm) edge. The special case of a trapezoidal weir with side slopes of 1:4 is known as a *Cippoletti weir* [12]. Each of the different weir types has an associated equation for determining the flow rate over the weir that is based on the depth of the upstream pool. Large water flows and small slopes where the water can be dammed and the measuring overflows are measured are an appropriate point at an adequate distance upstream from the weir. The head is measured as the difference in level of the pool as compared to bottom point of the weir, i.e., at the crest, as shown in Fig. I/3.1.5-3 (top part) with a proper measuring instrument. Head should be chosen in such a way that 35 mm $< h <$ 300 mm. There should be a sufficiently large stilling basin ahead of the weir, to restrict the upstream velocity to within around 0.01 m/s. In order to avoid a wall effect on the flow pattern, the width and depth just ahead of the weir should be adequately large. In the case of a notch the flow breaks clear from the sharp edge of the notch with an air pocket maintained immediately beyond and below the weir plate [12]. The channel downstream is made adequately large so as to provide adequate clearance between the weirs to downstream.

- *Rectangular or trapezoidal (Cippoletti) weirs:* Both these types of weirs are depicted in Fig. I/3.1.5-3. Both rectangular and trapezoidal/Cippoletti weirs are used for larger flows. Because of the side containment of the overflow stream in a rectangular weir without contractions the air supply can become restricted. Therefore

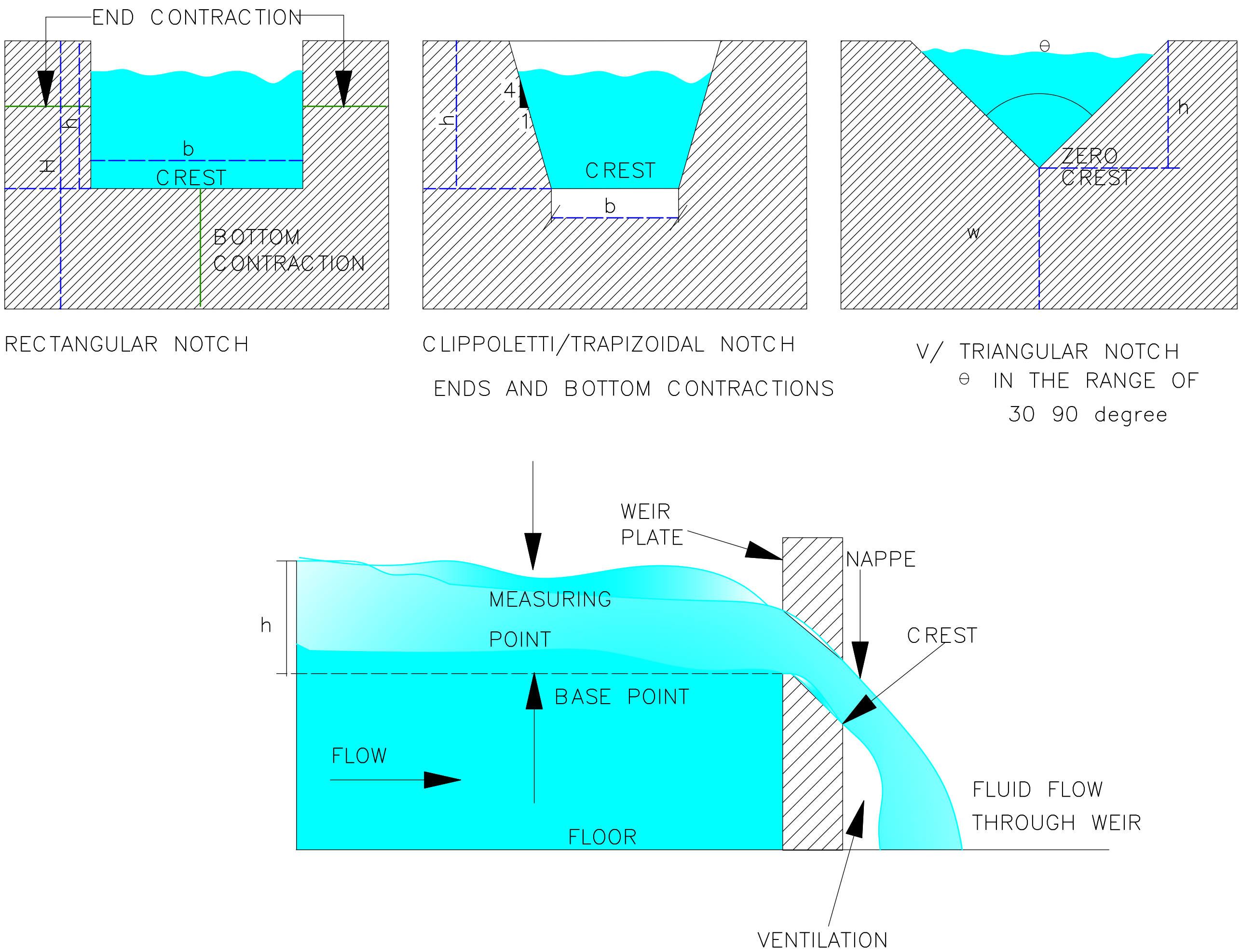


FIGURE I/3.1.5-3 Weir.

ventilation must be assured. For rectangular weirs for proper measurement, measurement height at the upstream level is kept at four times per hour. For rectangular and Cippoletti weirs, the crest should be carefully leveled. In the case of a rectangular weir 20:1 turndown is possible.

- *V-notch:* V-notch weirs find their applications in smaller flows and these are suitable for flow rates between 2 and 100 L/s and it is possible to get turndown of 100:1 [1]. These weirs have discharge coefficient μ as a function of the ratio of the overflow height h to the weir height w, shown in Fig. I/3.1.5-3, and normally the value is selected from a given curve. However for 30 degrees a V-notch weir has a practically constant coefficient from 11.4 to 1140 L/min [12]. The coefficient increases roughly 2% for flow down to 1 GPM (3.8 L/min) and changes relatively little for flow up to 500 GPM (1893 L/min). For a notch angle up to 90 degrees, flow varies as the tangent of half the notch angle. As stated earlier these are selected with a notch angle θ lying between 30 and 90 degrees as shown in Fig. I/3.1.5-3, beyond which a notch is not recommended.
- *Equations for calculations:* A general equation for a weir is given by Eq. (I/3.1.5-4). Here q_v stands for flow rate (volume), C is coefficient dependent on crest and approach condition (and a constant dependent on unit chosen also, as will be clear from subsequent

equations), h and b represent the width and head of the crest, respectively, and the exponent is dependent on weir type/opening.

$$q_v = Cbh^m \qquad \text{(I/3.1.5-4)}$$

In imperial units, h and b are in feet; whereas in SI, h and b are in cm (i.e., 1/100th m).

For **both sides of a contracted rectangular weir**

$$q_v = 3.33(b - 0.2h)\cdot h^{1.5} \text{ in FPS \&}$$
$$q_v = 0.0184(b - 0.2h)\cdot h^{1.5} \text{ in cm.} \qquad \text{(I/3.1.5-5)}$$

For a **Cippoletti weir**

$$q_v = 3.367b\cdot h^{1.5} \text{ in FPS \&}$$
$$q_v = 0.0186b\cdot h^{1.5} \text{ in cm.} \qquad \text{(I/3.1.5-6)}$$

For a **v-notch** Weir (coefficient μ dependent on h:w)

$$q_v = 2.48\cdot \mu \tan(\theta/2)\cdot h^{2.5} \text{ in FPS \&}$$
$$q_v = 0.533\cdot \mu(2g)^{0.5}\cdot \tan(\theta/2)\cdot h^{2.5} \qquad \text{(I/3.1.5-7)}$$

in Eq. (I/3.1.5-7), coefficient μ is kept for generalized cases and h is in meters.

3. **Sensing:** Once the primary device is put in place and the relation between flow rate and head is established by any of the formulas discussed above, the level can now be sensed by:
   - *Direct measurement method:* float type level sensing;
   - *Indirect measurement method:* hydrostatic pressure measurement, noncontact level sensing such as ultrasonic level sensor or by hydrostatic pressure measurement using a bubbler. All these are discussed in detail below.

With this the discussions on open-channel flow measurement principles come to an end. Discussions on the principles and types of fluid flow measurement are also concluded and we now tackle solid flow.

3.2.0 Solid Flow Measurement Types and Principles

Solid flow measurement is quite different from fluid flow measurement. It is very much dependent on material characteristics, associated feeding equipment, as well as both combined. Except for a small number of measurements such as nucleonic solid flow measurement, most measurements include associated equipment and feeding systems. Therefore, if for a particular solid the proper feeding system is not chosen there is the possibility of inaccurate measurement, leakage, and jamming of the whole system. Thus, in the case of most fluid measurements, a particular behavior of the fluid is utilized in measurement of flow. Solid flow characteristics are extremely difficult to evaluate and in the majority of cases one has to depend on trials. Therefore, it is imperative that bins/hoppers, feeding systems, and solid flow-measuring systems are designed in a coordinated and integrated manner, taking into consideration various characteristics of the material such as density, lump/particle size, flow-ability/tendency to get compacted, moisture content, temperature, hazardous properties, etc. However, in reality this equipment is not procured for trials only. With experience with commonly used materials it is possible to select the proper bin and feeding system, e.g., for a dry cement process equipment design that can be done without the need for a trial, including the feeding system for ore in lumps, raw mill feed system, kiln feed system, clinker handling of fine cement handling, etc. Layout may also play a role, e.g., during my tenure in the cement industry, I found different measuring arrangements were done in different plants for a kiln feed system, e.g., loss in weight method, impact scale, covered weigh feeder, and even a nucleonic system. These were done in mostly for layout and feed considerations. In solid flow measurement, the weighing system is used extensively to measure dry bulk material flow rates. When compared with volumetric flow, weighing can measure a material quantity directly, without any

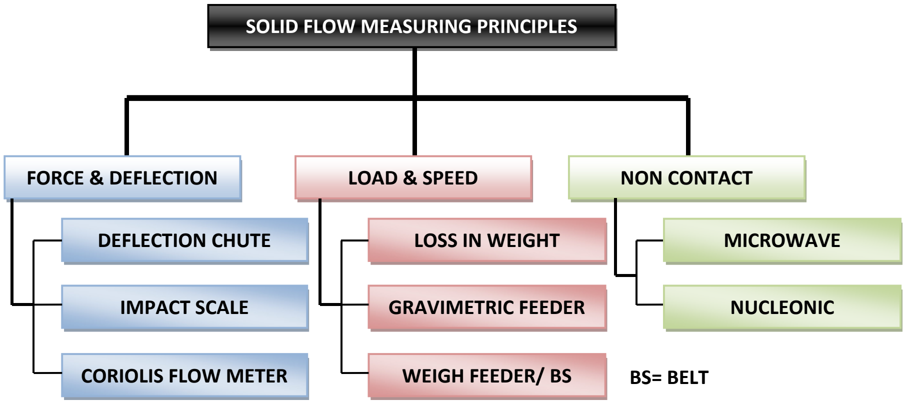


FIGURE 1/3.2.0–1 General classification of solid flow measurement.

requirement for a correction factor pertinent to the material's bulk density. There are some weighing systems which do not make contact with the material so they are suitable for corrosive materials and operating in corrosive environments. Weighing systems can take any of several forms, but in most cases one or more load cells are deployed. Load cell accuracy is of immense importance. In addition, there are other factors such as load factor, large temperature change, vibration, shock loading, and environmental forces such as wind loading, moisture, etc. that are also important. In many systems like weigh feeders and gravimetric feeders, accurate speed measurement is essential. All these discussed measurements use mainly load cells/strain gages.

There are also other means of solid flow measurements such as microwave and nucleonic measurement. In addition to some specific application area, i.e., pharmaceutical industries, food industries, there are filling machines, etc these solid flow meters find their applications in many other industries such as cement industry. From the above discussions it is clear that there are a number of types of solid flow measurements. Broadly, solid flow measurement methods can be classified as shown in Fig. I/3.2.0-1. In this book the same sequence will be followed for discussing principles of operation of solid flow meters.

3.2.1 SOLID FLOW METERS BASED ON FORCE AND DEFLECTION PRINCIPLES

It has been found that there are some risks of confusion between two types of solid flow meters: impact scale (impact flow) meters and centripetal force (deflection chute) meters [42]. Also, there is another kind of flow meter which works on the Coriolis principle. The commonality among the three is that direct force due to weight (load) is not measured, instead force where mass of solid flow is a function is measured. Also, in these cases deflection due to solid flow is measured. The basic physics of measurements of all three types are depicted in Fig. I/3.2.1-1. Of these three types, the impact scale is most commonly used in major industries such as cement and steel plants. We now look into the details of these systems.

In order to understand solid flow metering it is necessary to have some knowledge of the commonly used terms which are elaborated on in Figs. I/3.2.1-2–I/3.2.1-4.

These terms will be frequently used in Chapter VIII while discussing material properties. Let the discussions start with deflection chute.

1. **Deflection chute/centripetal flow meter:** The discussion starts with reference to Fig. I/3.2.1-1.

   This is often referred to as a centripetal solid flow meter. Centripetal force is an inward force necessary to keep an object moving in a curved path. When the object moves in a curved path (with radius R), with velocity v there will be centripetal acceleration. According to Newton's second law, centripetal acceleration gives rise to centripetal force

$$F = mv^2/R \qquad (I/3.2.1.1\text{-}1)$$

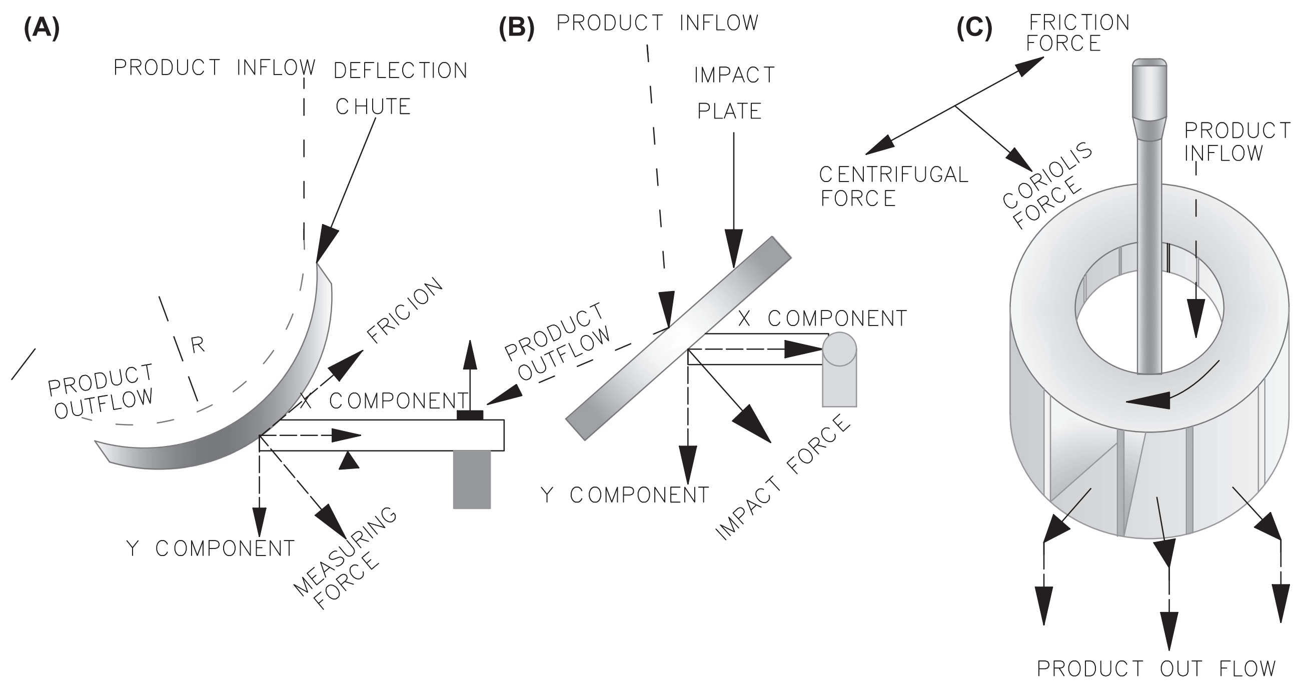


FIGURE I/3.2.1-1 Force and deflection type solid flow meter. (A) Deflection chute/centripetal force. (B) Impact scale. (C) Coriolis meter.

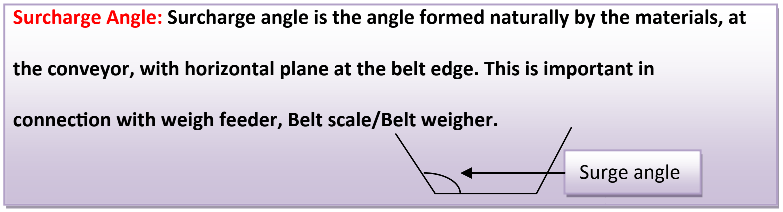


FIGURE I/3.2.1-2 Surcharge angle.

Hygroscopic material: **The ability of materials to attract and hold moisture is referred to a hygroscopic material. This can be done by absorption or adsorption. This change material property also.**

FIGURE I/3.2.1-3 Hygroscopic material.

As long as the velocity and radius of the curve are fixed, F is proportional to mass flow. It is independent of density and particle size. In centripetal force, meter product flow drops vertically through a guide parallel to the sensing plate into the meter and is directed into a curved measurement chute where the product slides through the curved chute of radius R. The flow meter works on the reactive force. The product flow creates a measurement force and friction force. As shown in Fig. I/3.2.1.1-1A, with the help of a fulcrum this force can be measured with the load cell. The location of the transducer is very important for this measurement [43]. Centripetal solid flow meters offer high accuracy (0.25% reading) [44], but are not suitable for sticky materials which may begin to build up on the sensing plate causing the signal to drift. It is easier for installation and calibration,

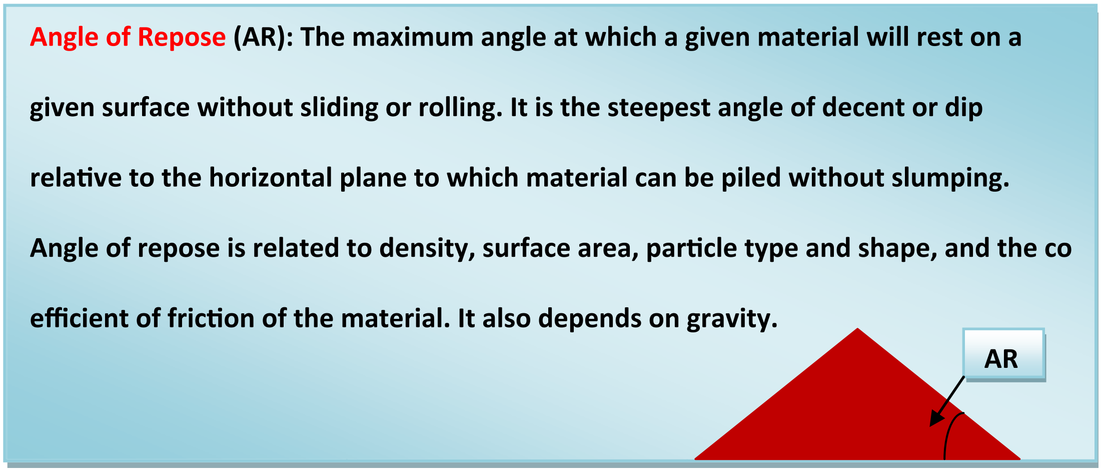


FIGURE I/3.2.1-4 Angle of repose (AR).

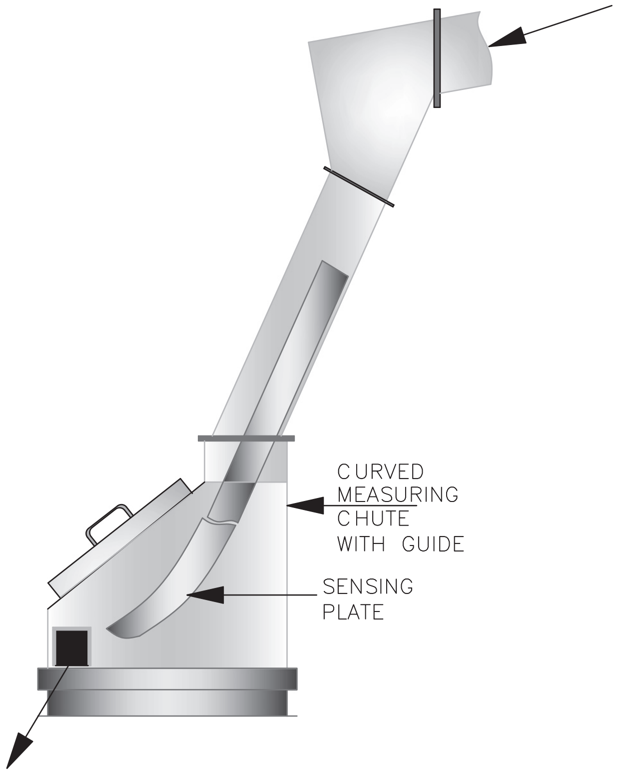


FIGURE I/3.2.1.1-1 Centripetal flow meter (deflection chute).

and it offers dust-tight enclosure. Finally, the signal is electronically processed to produce flow rate and total weight values.

2. **Impact scale/meter:** In an impact scale solid flow meter or impact flow meter (as these are often called), there is a flow guiding system. This guides the material through an in-feed pipe or chute and creates a specific trajectory for striking the impact or sensing plate. The meter responds to the force of the material striking the sensing/deflection plate. This striking force has two components: horizontal and vertical. The horizontal force, which is dependent on the mass of the particle, velocity of the particle, energy absorption capacity of the particle, and angle of the particle against the impact plate, is sensed and measured. In an impact meter such deflection due to a horizontal component is sensed and converted into an electrical signal. Depending on the type of sensing deployed there are two versions of impact meters.
   - *Load cell type:* When the horizontal deflection is sensed and measured by one or more load cells to produce an electrical output this is a load cell sensing impact scale (e.g., SITRANS WF 100/200 of Siemens where there are parallelogram load cells with a strain gage).
   - *LVDT type:* This is another type where a linear variable differential transformer (LVDT) is deployed to measure horizontal deflection. These are LVDT type impact scales (e.g., SITRANS WF 300).

   Both are detailed in Fig. I/3.2.1.2-1. Impact flow meters can handle a wide range of flow rates. The accuracy or repeatability of an impact scale is unaffected by material

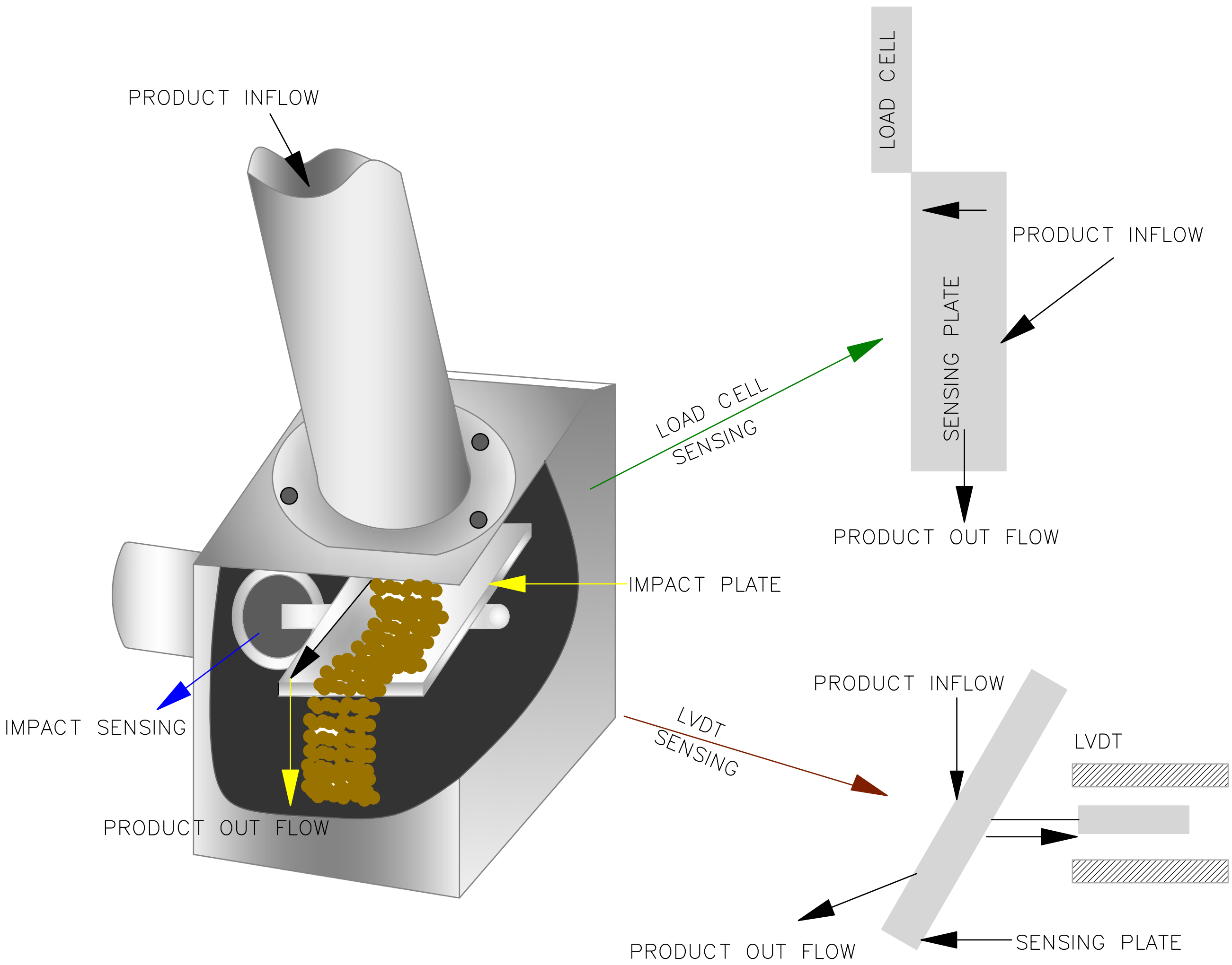


FIGURE I/3.2.1.2-1 Impact scale FM. *Based on an idea from Solid Flow Meter 6, Siemens Catalog, Siemens AG, 2016, http://www.automation.siemens.com/sc-static/catalogs/catalog/wt/WT10/en/WT10_en_kap06.pdf.*

buildup on the sensing plate because only the horizontal component causes deflection on the sensor which is sensed and converted into an electrical signal. It is available in a dust-tight enclosure [45].

On account of these advantages this flow meter is often applied to measure kiln feed, which is the most important parameter in cement industries.

3. **Coriolis solid FM:** The basic physics behind the Coriolis meter has been described in Fig. I/3.2.1-1. As shown there, Coriolis force acts perpendicular to the direction of motion of the particle. In connection with fluid measurement, it has been established that Coriolis force is directly proportional to the torque, for which there is acceleration in the particle moving with the circumferential velocity in a rotating system. Reader may compare this with Coriolis principle discussed in Section 3.1.4 in this chapter. In a Coriolis mass flow meter, there is a rotating measuring wheel with several vertical guide vanes surrounding a central deflection cone, as shown in Fig. I/3.2.1.3-1.

   Also shown in the figure are the feeding system (which feeds the material in the measuring wheel) and a central outlet below the wheel which provides the flow path for the bulk solid to be measured. The measuring wheel is mounted on a drive shaft, which is extended upwards, outside the enclosure, from the deflection cone in the enclosure.

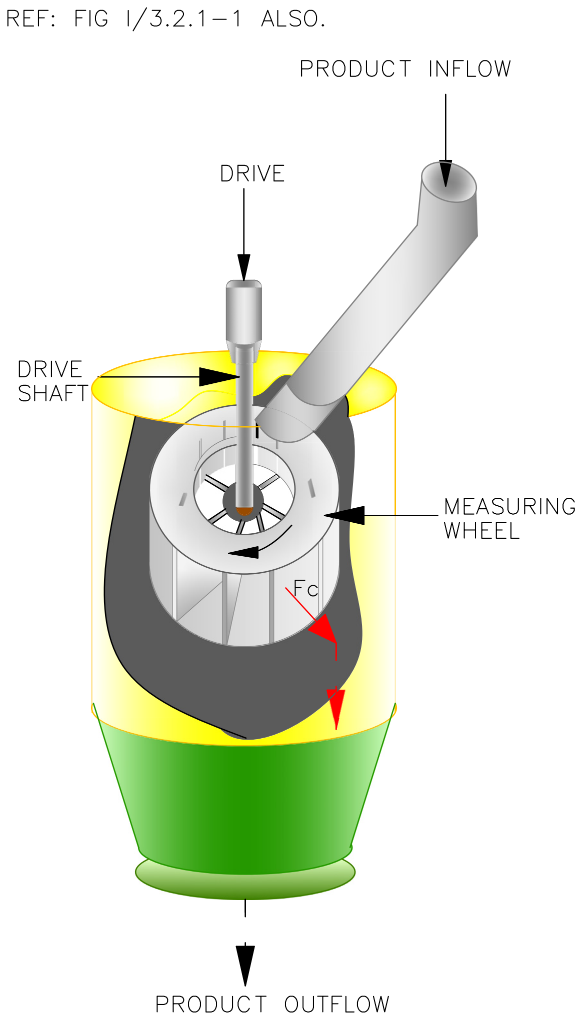


FIGURE I/3.2.1.3-1 Coriolis solid FM.

The measuring system comprising a load cell to measure torque is coupled with a motor. An electronic unit is connected to the load cell for further signal processing. Any single particle moving across the vanes of the rotor, due to motion, exerts a Coriolis force on the rotor vane, which produces a measurable torque.

The motor of the mass flow meter drives the shaft, causing the measuring wheel to rotate at a constant angular velocity. Material flows downward through the inlet into the top of the wheel and the deflection cone diverts the particles outward in the radial direction. As the particles move along the vertical guide vanes, due to circular motion, they are accelerated in the circumferential direction. As a result of this there are three forces on the particles as they move along the guide vanes.

- Centrifugal force acts in the radial direction along the surface.
- Frictional force acts in the opposite direction with a magnitude equal to the centrifugal force on the surface.
- Coriolis force is in a direction perpendicular to the surface.

  Therefore, centrifugal force and frictional force along the surface not only cancel each other but also do not have any effect on the Coriolis force as it is perpendicular to the other forces.

The drive input into the drive shaft is equal to the energy imparted to the material as it passes over the guide vanes:

$$E = \int dE = \int T \cdot \omega \cdot dt \qquad \text{(I/3.2.1-1)}$$

where E is the energy imparted to the material, T is the drive torque, ω is the angular velocity, dt is time change, and dE is the change in energy. The energy required to move a particle with mass dm out of the measuring wheel is:

$$dE = dm \cdot \omega^2 \cdot R^2 (\text{ref: Section 3.1.4}) \qquad \text{(I/3.2.1-2)}$$

where R is the radius of the measuring wheel. From these equations, it follows that the drive torque T can be measured as:

$$T = q_m \cdot \omega \cdot R^2 \qquad \text{(I/3.2.1-3)}$$

where q_m is the mass flow rate. Therefore, T, which depends on the Coriolis force, is directly proportional to the mass flow rate q_m. Thus, by measuring the torque, the Coriolis mass flow meter accurately measures the mass flow rate. This measuring technique assures that frictional forces between the material and the measuring wheel or between different layers of material do not influence the mass flow measurement [46]. Also, various physical properties like density, friction and impact coefficients, particle size, and moisture

content do not influence the accuracy or sensitivity of the meter. Coriolis solid flow meters are well suited for high flow rate and high accuracy applications [43]. The Coriolis design may not be suitable for abrasive materials or large particle sizes. Because of abrasive materials, vanes may become worn out and large particle sizes may cause jamming or clogging. At times a high voltage requirement for the electric motor may be a problem on account of the lack of availability of high voltage.

3.2.2 SOLID FLOW METERS BASED ON LOAD SPEED/TIME PRINCIPLES

Major solid flow measurements fall under this category. In this category the weight rather than the mass of solid materials is measured. These measurements help in finding the load due to the weight of the materials. In certain cases, of course, load cells are not deployed, i.e., platform and overload type measurements of Acrison, where flexure movements are used to calculate the load, without any load cell. Also, in the volumetric feeding method, volume flow is determined by simply relying on the volumetric properties of the feeder to deliver product at a constant rate. Therefore, when bulk density is known then mass flow can be computed. However on account of the high accuracy requirements of feeding of some systems, e.g., pharmaceutical processes, the gravimetric feeding principle via loss in weight feeding is mandatory. There are three major differences between volumetric and gravimetric feeding systems. These include but are not limited to the following.

- The volumetric feeding system is open loop, and hence is not so precise as there is no feedback to take care of instantaneous changes. Gravimetric feeders have feedback control to cater to these requirements more precisely. Naturally, a gravimetric feeding system provides higher accuracy.
- Volumetric feeders have simple controls, whereas gravimetric feeding systems have a complex control system. Naturally, in cost comparisons, volumetric feeders are much less costly than their gravimetric counterparts.
- Maintenance of volumetric feeding is totally different from maintenance of a gravimetric feeding system as it demands more skill to recognize the complex diagnostics associated with it.

We now concentrate on dynamic weighing systems. The main system involvement is related to a dynamic weighing system, as very briefly shown in Fig. I/3.2.2-1. A dynamic weighing system is quite vast, and only the parts utilized in major industries and covered in this book are shown here. Interested readers may refer to Ref. [47] for further details. In this section, the basic principles of loss in weight, gravimetric feeder, belt scale/belt weigher/weigh feeder are covered, filling machines will also be covered and the remainder are covered in Chapter VIII. The discussion starts with the loss in weight method.

1. **Loss in weight (LIW), Gain in weight (GIW) and gravimetric feeder:** Loss of weight is one of the gravity feeding methods. The other method could be a weigh feeder. A weigh feeder and belt scale/belt weigher is used extensively in cement, steel, and other industrial plants and so weigh feeders will be discussed separately. However, as gravimetric feeders in power plants have a different significance they are discussed here. Since LIW is more popular it is discussed here. Like loss in weight method there is gain in weight method in solid flow measurement also. Gain in weight (GIW) has been discussed at length in chapter VIII.
    - *Loss in weight method:* Loss in weight feeding normally regulates the dispensing of material by weight into a process at a precise rate in a controlled manner. Mostly these are used in a batch process, e.g., pharmaceutical industries, food industries etc., but they also have applications in other industries, e.g., I have used the loss in weight method (with minor modifications) in a kiln feed system in Jordan. The target feed rate, which may vary from

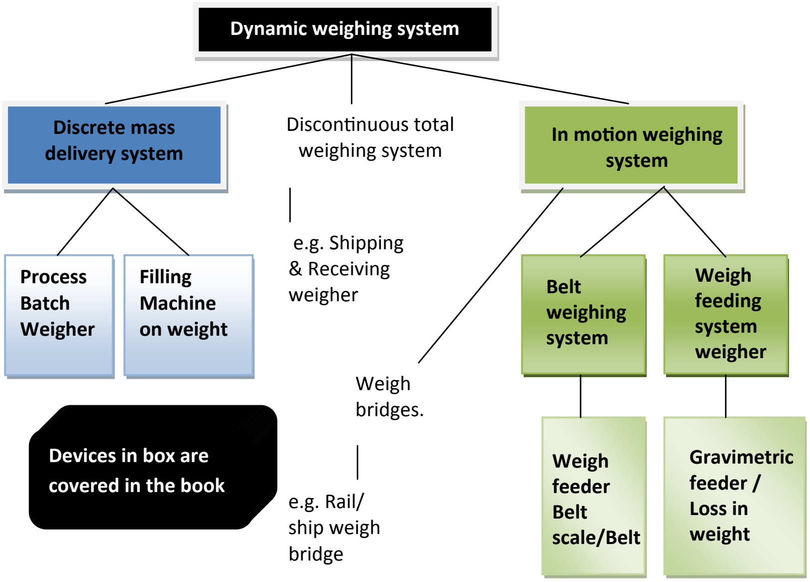


FIGURE I/3.2.2-1 Dynamic weighing system.

very small quantities (gram/second) to large quantities (e.g., tons/hour), is referred to as the loss of weight set point. A typical loss in weight method of measurement has been depicted in Fig. I/3.2.2.1-1.

The operation of a loss in weight system is divided into the metering, refilling, and settling phases. In the metering phase, the actual conveying rate and volume of material are measured continuously gravimetrically with a high-resolution weighing system, which is of interest here. The weigh control system finds the load signal from the load cell to compare against a defined set point and controls the conveying rate of the small feeder. Gravimetric feeding is used for the loss in weight (LIW) method also. Here the designed system utilizes a weighing system (e.g., with the help of a load cell) to weigh the whole hopper/feeder system, together with its contents (the product to be fed) [47]. The basic loss of weight principle is to discharge the product at a constant loss of weight per unit time t. The product in the hopper weighing W, is discharged by the feeder in such a manner that dw/dt is always constant and this represents the feed rate as shown in Fig. I/3.2.2.1-1. For this dw the typical loss of weight control system configuration, as shown in Fig. I/3.2.2.1-1, has been incorporated. The associated control system reads both the load cell signal as well as the feeder speed (with the help of a speed sensor which could simply be a tachometer). Based on the target set point, a microcontroller continuously compares and computes the load signal and derives the set point. This speed set point is compared with the actual speed signal to produce an output signal to control the motor speed through the drive control system, i.e., feeder speed control. Some controllers execute the operation on the totalized quantity of material actually fed over a period of time for target and calculation to execute incremental corrective changes to the feeder speed to optimize long-term feeder accuracy [47]. As shown in Fig. I/3.2.2.1-1, the filling part will take the help of volumetric method with the required feeder type, e.g., screw feeder.

As stated earlier, volumetric feeding relies on the volumetric properties of the feeder to deliver product at a constant rate. Since there is no feedback, it is an open loop and cannot claim high accuracy. Also material density variations (which will alter the weight of the material delivered),

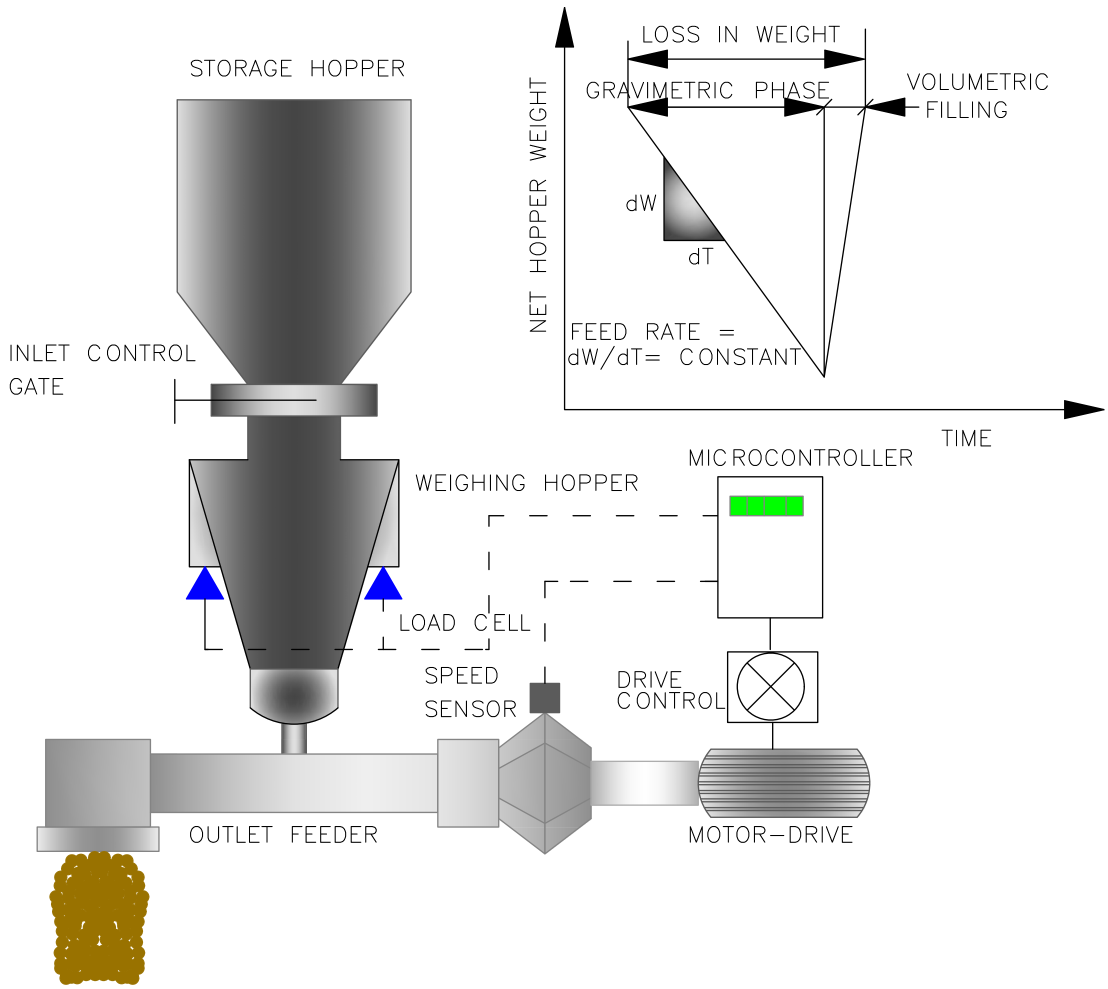


FIGURE I/3.2.2.1-1 Loss in weight.

discrepancies in volumetric delivery rate (due to speed variations in an open loop system), and material flow inconsistencies within the feeder mechanism, make volumetric system less accurate and inconsistent. For this reason the volumetric system is not used for flow measurement but may be used for filling as shown. Thus, in this example both volumetric and gravimetric systems are utilized.

- *Gravimetric feeder:* From earlier discussions it is clear that for meeting precise requirements with higher accuracy, gravimetric feeding is necessary. In fossil fuel power plants, precise control of fuel feed cannot be overstated. On account of sizing differences and moisture impact coal properties vary greatly, including bulk density. Therefore, for precise fuel flow control, gravimetric feeders are recommended as they are not affected by bulk density.

A gravimetric feeder weighs material on a belt between two fixed points, determining the span, located in the feeder body. A roller, at the midpoint of the span, supports half the weight on the span. This roller is supported at two ends by a set of precision load cells. Therefore load cells measure the weight supported. In modern digital technology, with the help of a microprocessor the outputs of each load cell are added to obtain total *weight per unit of belt length*. The speed of the belt is also sensed by speed sensor(s) as discussed earlier. Through meter calibration and a calibrating factor, the rotational speed of the motor is converted into

linear speed. So multiplying the two outputs along with the meter fact will yield the feeder rate. In the case of fossil fuel power plants, this feed rate is compared with the demand signal generated from the boiler master control. As further details on boiler controls are beyond the scope of this book they are not discussed here—for detailed discussions on boiler controls and fuel flow control Ref. [24] may be referred to. In gravimetric feeders, accuracies of better than 0.5% reading are obtainable.

2. **Weigh feeder/belt scale/belt weigher:** With a weigh feeder or weigh belt/belt scale/belt weigher, weighing of continuous, controlled product flow is possible. The bulk material is transported through the weighing section of the conveying feeder supported in a feeder frame. The feed rate is calculated from the load or weight and the belt speed for calculating mass flow and cumulative weight. From an instrumentation and control point of view functionally these devices provide:
   - bulk material weighing and conveyor speed;
   - solid flow measurement;
   - belt speed control (weigh feeder);
   - totalized flow measurement.

   Basically there is not much difference between the two so far as the principle of operation is concerned. However, from an application point of view there are some differences. The basic components/parts of a weigh feeder and belt scale/belt weigher are illustrated in Table I/3.2.2.2-1.

   The weighing section measures the weight of material (with tare) of a given length (unit length). As the conveyor moves it has a linear speed. By measuring the speed of the conveyor at the tail pulley the rotational speed of the conveyor is known. For a known pulley diameter the linear speed of the belt can be inferred. Therefore, multiplying two signals one gets $\boldsymbol{(W/length)\cdot(length/second) = W/S}$, i.e., mass flow of solid. In this type of measurement accurate transmission of weight data is important. The load cell should only measure the vertical load component (see Fig. I/3.2.2.2-1).

   - *Weigh feeder:* As stated above, in a weigh feeder solid mass flow is measured rather than computed, by measuring the weight of the flowing material on a feeder and the feeder speed. In the case of a weigh feeder, the speed of the feeder/conveyor (or material load on the belt/feeder) is controlled to meet the target set point. An associated controller provides the totalized output.

TABLE I/3.2.2.2-1 Components/Parts of Weigh Feeder/Belt Scale/Belt Weigher

Sections	Components/Parts	Function	Remarks
Conveyor[a]	Belt, pulleys, idler frame, inlet skirt accessories, e.g., drift switch, rope switch	Material conveying with protections	Common to weigh feeder and belt scale/belt weigher
Weighing	Weigh bridge, scale	Weighing tare and materials in a given section	As above
Speed sensing	Speed sensor and encoders	Speed measurement	As above
Electronic section	Integrator, controller	Computing rate and totalized flow	Controller for weigh feeder to meet the target set point
Drive[a]	Motor with gear trains, drive control (variable frequency drive—VFD)	For driving force for conveyor, and drive control to control the speed of conveyor	Drive control (VFD) for weigh feeder only

[a] *To meet Conveyor Equipment Manufacturer Association (CEMA) standard.*

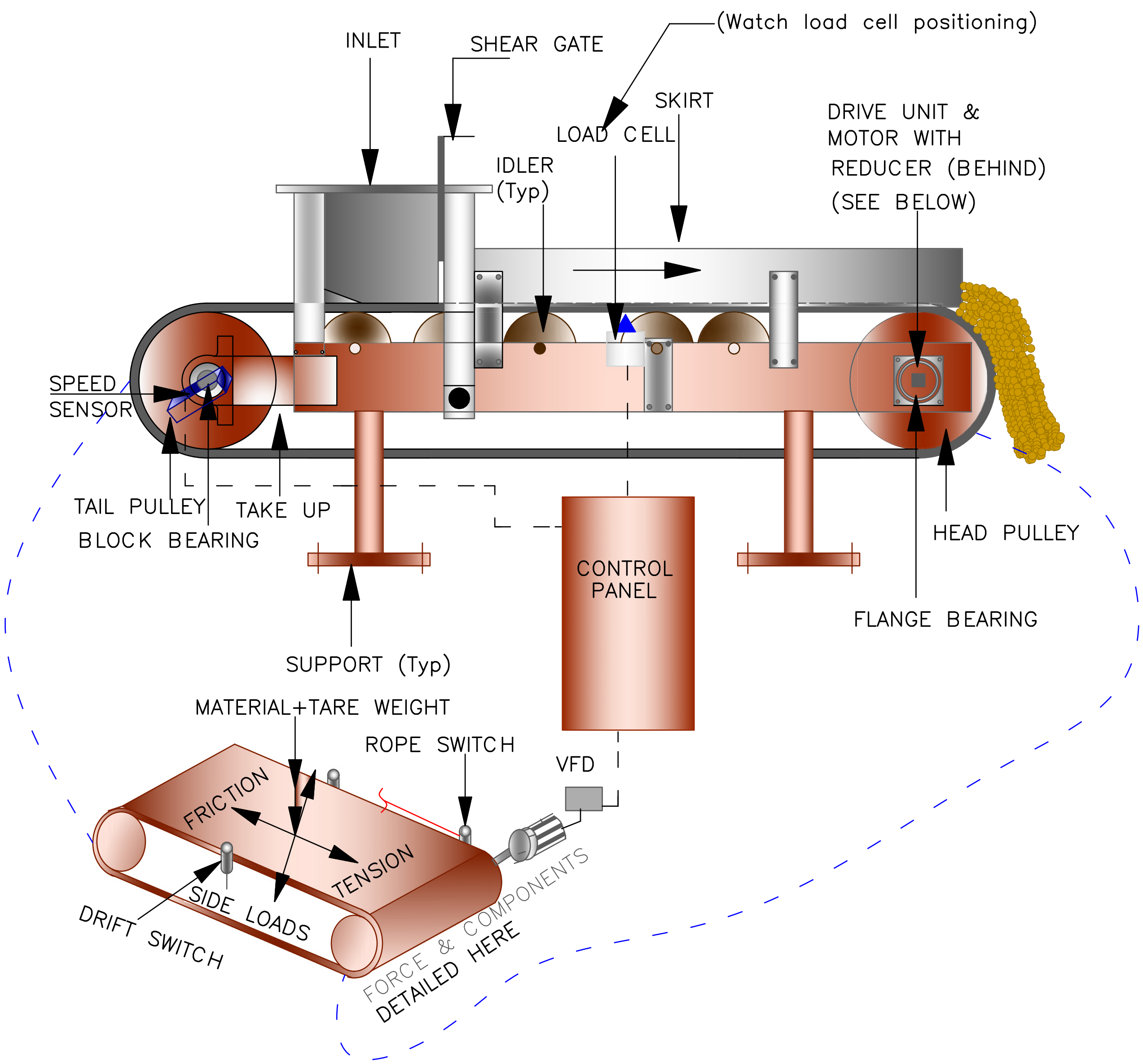


FIGURE I/3.2.2.2-1 Weigh feeder.

Weigh feeder details are presented in Fig. I/3.2.2.2-1 with all components already detailed in Table I/3.2.2.2-1. The rate flow, totalized flow, as well as load/speed data can be obtained through an integrator and associated electronics. Additionally, the speed of the drive can be controlled with a variable-frequency drive (VFD).

- *Belt scale/belt weigher:* A belt scale/belt weigher or weigh belt is similar to a weigh feeder. Here the conveyor is run at a constant speed, i.e., by a constant speed motor, unlike a weigh feeder where a variable-speed drive is deployed. The various components are already detailed in Table I/3.2.2.2-1 and Fig. I/3.2.2.2-1. The rate flow and totalized flow, as well as the load/speed data, can be obtained through an integrator and associated electronics.

Solid flow can also be measured with the help of noncontact type devices, which we now explore.

3.2.3 NONCONTACT TYPE SOLID FLOW MEASUREMENT

Like in fluid flow measurement, solid material flow can also be measured by noncontact methods. Radiation and microwave technologies are mostly used to measure solid flow in conveyors and flow pipes. In many industries there exist extreme measurement conditions, such as high temperature (e.g., a hot clinker), high pressure, high dust (as in the cement industry), or use of highly corrosive and abrasive media where it may be better to opt for noncontact solid flow measurement systems which offer a number of advantages. These advantages include the following.

- No obstructions to flow or buildup;
- No contact with the material to be measured;
- Easy to install, with end connections;
- Easy installation for retrofitting application;
- Totally enclosed construction;
- No moving parts;
- Free from wear, less maintenance;
- High availability and rugged design
- Stable measurement without recalibration;
- Easy servicing and on line maintenance;
- Versatile use as a flow meter, batch meter, etc. No moving parts.

However, in certain cases, such as in gamma radiation applications, safety requirements are necessary. In these applications good accuracy is also available. This discussion starts with radiation (non-nucleonic) type of solid flow measurement principles.

1. **Microwave type solid flow measurement:** The microwave measuring system consists of a flow tube/pipe, a sensor in the form of a transreceiver, along with a stainless steel pipe that acts as a waveguide for proper performance, and the necessary electronic unit. To mount the equipment, a hole for the mounting plug is first drilled into the conduit as shown in Fig. I/3.2.3.1-1.

   The sensor is installed in a pipeline wall. The transreceiver transmits a low-energy microwave at about 24 GHz to the particulate matter passing through a flow pipe. On account of the particulate matter there will be a reflection of the signal detected at the receiver in the sensor (transreceiver). There will be Doppler shift in the amplitude and frequency, i.e., the intensity of the reflected signal. The mass flow is determined by evaluating the frequency and amplitude changes during the measurement. The reflected Doppler shifted energy signal is a function of the velocity and flow quantity of the material [48]. The Doppler signal measured by the sensor is converted to a signal output of, e.g., 4–20 mADC signal. There will be a computing system utilizing a special algorithm to compute the mass flow rate as well as the totalized flow of solids. Particles at rest, such as deposits, do not influence the measurement. Also, the measurement system is virtually unaffected by pressure and temperature [49]. The measurement system is independent of the particle moving direction and can measure solid flow when the velocity is at least 0.1 m/s [50]. The measuring system can be used for solid flow measurements in vertical pipes (including gravity flow) and pneumatic feed lines. For larger pipes, a number of sensors may be necessary to get a better average of the particle flow profile. The measurement system can offer an accuracy of 2% FSD.
2. **Radiation (nucleonic) type solid flow measurement:** A radiation type solid flow meter is mostly used to measure solid flow in different conveyor types as illustrated in Fig. I/3.2.3.2-1 (left-hand part of the figure). This technology can also be used to determine the freefall flow in pipe lines (Fig. I/3.2.3.2-1 right-hand part). For this measurement radiation is generated and this is done with the help of a radioactive material whose energy is dependent on the load on the conveyor [51]. Normally Caesium-137 or Cobalt-60 isotope emitting focused [52] gamma rays are used to do this. This radiation is attenuated

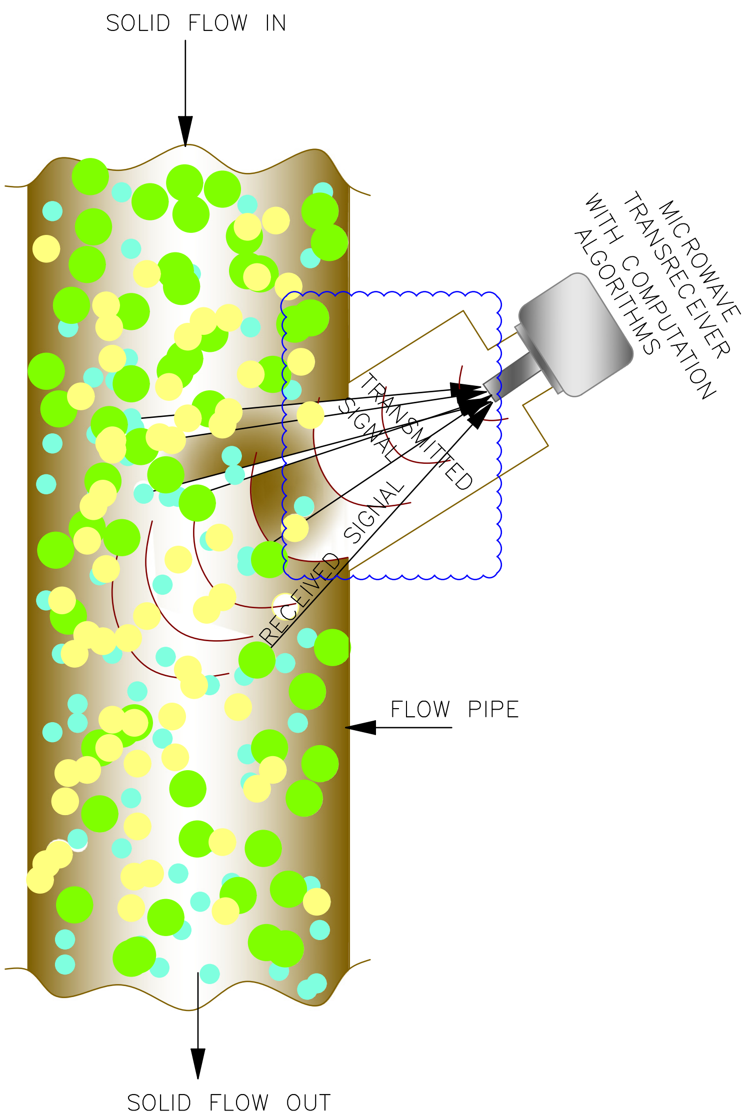


FIGURE I/3.2.3.1-1 Microwave solid FM.

when penetrating the conveyor belt and the medium. Thus the radiation is absorbed by the product on the belt and finally the attenuated radiation—the remainder is picked up by a detector (e.g., a scintillation counter) for further evaluation.

The radiation type measurement utilizes the physical law of the attenuation of gamma radiation passing through the product.

The remaining radiation picked up by the detector (scintillation counter) reflects the mass of the product being measured. Fig. I/3.2.3.2-2 illustrates the principle of measurement. As per the law of attenuation, the relation between the remaining attenuation, I, and source attenuation, I_0, is given by:

$$I = I_0 \cdot e^{-\mu'} \cdot \rho \cdot d$$

where I = remaining radiation (*load*); I_0 = source radiation; μ = absorption coefficient in cm^2/g; ρ = material bulk density in g/cm^3; and d = material height in cm.

The minus sign indicates the absorption by load material. The initial intensity I_0 is influenced by the product of bulk density of material and d material height (i.e., $\rho \cdot d$). Thus the measurement gives the

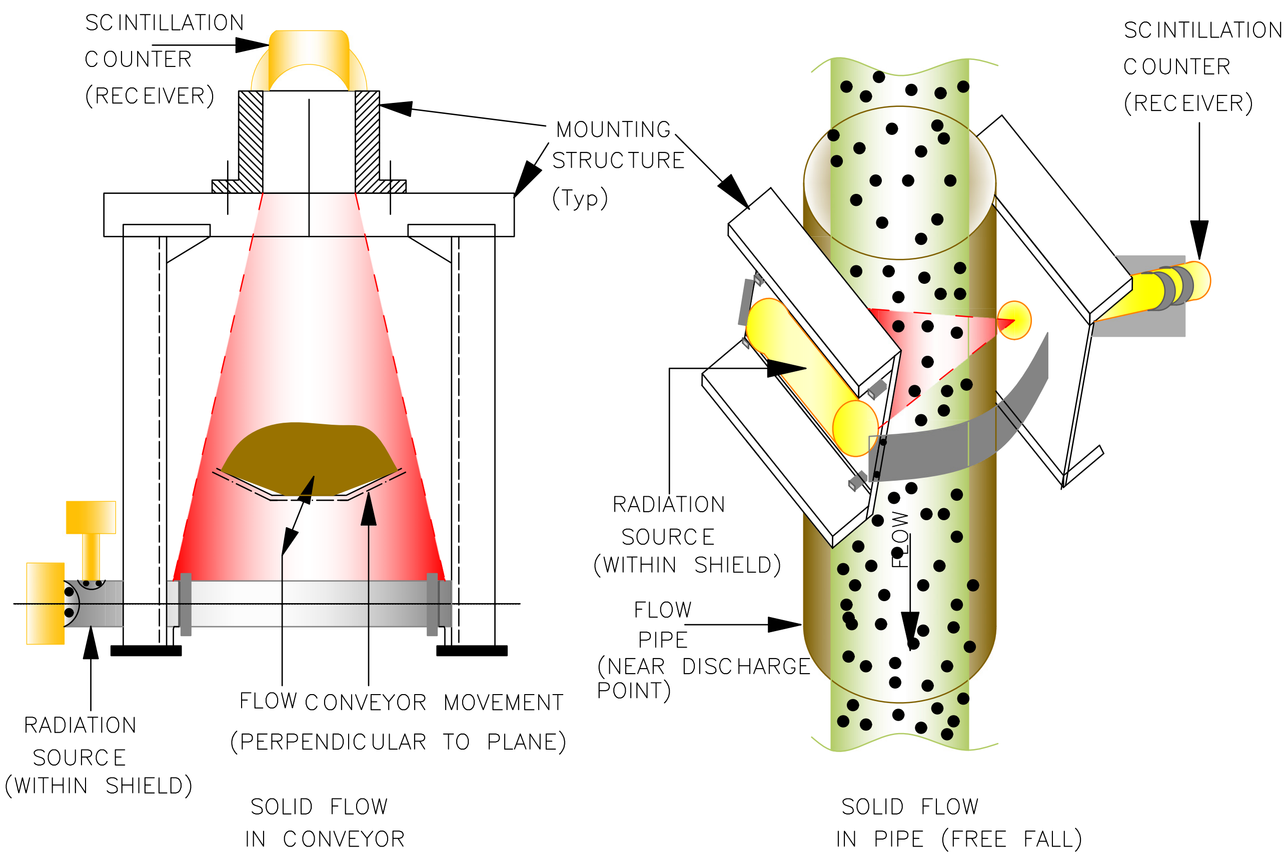


FIGURE I/3.2.3.2-1 Nucleonic solid FM. *Based on Bulk Flow Meter, Berthold Technologies, LB 442 Catalog, https://www.berthold.com/en/download/request/verify/ZH1Blytz04h5ORalPOsRNyNl0kG4euyizcN1Lzte1R8?destination=node/233.*

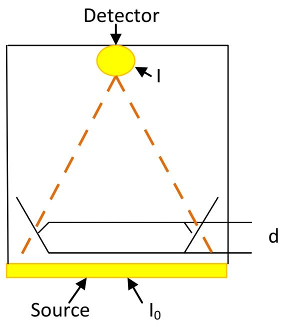


FIGURE I/3.2.3.2-2 Law of attenuation.

mass per unit of area. This variable is known as the weight per area [51,53] in g/cm^2. If this mass per unit of area is multiplied by the material width, the result is the mass over 1 m of the conveyor, the resultant will be mass. Therefore, multiplication by conveyor speed will give flow rate mass per time unit, e.g., tons per hour. Contamination of the product (being measured) or the pipeline wall by gamma radiation is not possible [51]. Thus in radiation time measurement, density is the main parameter measured and this, along with material height and solid mass flow rate, is computed in conjunction with a signal from the conveyor speed. The attenuation occurring during maximum conveyor throughput determines the choice of source. The measuring principle is very reliable and as indicated earlier is suitable in extreme process conditions because it measures contactless from outside, through the conveyor belt. The measuring system ensures maximum safety, reliability, and plant availability, independently of the medium and its properties [52]. On account of radiation, some precautions are necessary. Normally, a lead (Pb)-filled shielding container encloses the radiation source and is kept locked. The applicable standard normally followed is ISO 2919.

As shown on the right-hand side of Fig. I/3.2.3.2-1, the same principle can be applied for measuring free fall solid flow. Normally such measurements are carried out near the discharge point/chute [52]. With this, the discussions on solid flow measurement is concluded.

So far discussions have been on either fluid or solid flow, however there are flows where there are solids mixed in liquids, making it very challenging for measurement. Such slurry flow measurements will be dealt with in the following sections.

3.3.0 Slurry Flow Measurement Types and Principles

Slurry flow measurement is always a challenging issue. Slurry flow does not only include liquids with suspended solids. In mining applications slurries are frequently encountered, but there are other industrial applications where slurry flows are found such as alumina plants, chemical plants, food industries, pulp and paper, sewage, etc. The solids may be fine or coarse, similarly viscosities may be different. To study slurry flow one needs to have a clear idea behind the physical and chemical behavior of materials. In this connection, rheology, described in Fig. I/1.1.2-9, plays an important role. Rheology is mainly applicable to substances with complex structures, i.e., mud, sludge, emulsion, suspension, polymers, and many other biological materials, where solid flows with deformed elasticity. For viscoelastic materials time is an important factor; as the name implies, this is the study of both elasticity and viscosity and is elaborated on in Chapter VII. This chapter also deals with complex fluids such as flow of chocolate, mayonnaise have been dealt. On account of diluteness of solids in the liquid violates the compositional approach in the liquid and liquid flow analysis. So, sediment-laden flows generally create several. The performance of pumps is also affected by sediment-laden flow [54]. The principles of operation of all meter types used in slurry flow have already been covered and hence are not repeated here, rather in this subsection types of meters and their selection are dealt with. It is therefore important to know the characteristic features of slurry flow and complex fluid.

3.3.1 MAJOR CHARACTERISTIC FEATURES OF SLURRY FLOW AND ITS EFFECTS

There a number of characteristic features of slurry flow which are very important in meter selection as listed below.

1. **Contents and properties of solids present:** Major issues here include particle size, mechanical and chemical nature of the solid, and the percentage of solids in the medium. When the solids are fine there will be less noise and abrasiveness as compared with coarse solids. Also, these influence the physical nature of the slurry, e.g., coal—oil-water suspensions show an increase in viscosity with a decrease in coal size [55]. Alumina slurry is extremely abrasive and creates huge fluctuations in output. The solids percentage and particle sizes play an important role in meter selection.
2. **Chemical properties of the fluid:** The importance of the chemical composition of the fluid cannot be overestimated; for selection of appropriate flow meters this is crucial. When an electromagnetic flow meter is chosen, if the slurry the improperly mixed there is the possibility of wide variations in conductivity, which will degrade the performance of the meter. For an abrasive material a soft lining is suitable, however this is unsuitable for corrosive materials. A combination of both may call for the use of a ceramic lining [56]. Slurry properties, like flow density and viscosity, have effects on the flow properties in terms of flow velocity, total impact energy, etc. The total impact energy of the media and power draw also increase with slurry density and viscosity [57].
3. **Flow velocity and flow profile:** Velocity and flow profile play a major role in slurry flow. It is quite obvious for abrasive slurry flow that if the velocity is high then there will be a greater chance of meter wear, especially for the lining of an electromagnetic flow meter. Therefore, in many cases the velocity is kept relatively low (<2.5 m/s), but this increases solid

settlement at the bottom. Obviously, such settlement can be avoided in vertical flow. There are different slurry hydraulic flow conditions observed in experiments, e.g., fly ash slurry study; these are homogeneous, intermediate, and saltation flow (a type of loose material or particle transport by fluids) depending on various properties of the suspensions (such as solid concentration, density, viscosity). When slurry velocity decreases, the settling tendency of the particles causes a distortion to the concentration profile and flow. With solid settlement at the bottom, there may be some skewness of the velocity profile. This will result in the top half velocity being greater than that in the bottom half. There may be skewness both in concentration as well as in velocity profile, causing the flow to become more and more heterogeneous. For complex fluid knowledge on various fluid properties for non Newtonian fluid (Section 1.1.2.5) is important.

3.3.2 FLOW METER TYPES FOR SLURRY FLOW

There are many instruments used for slurry applications, including but not limited to the following.

- Magnetic flow meter;
- Ultrasonic flow meter;
- Wedge meter;
- 90 degrees elbow;
- Multivariable transmitter;
- Coriolis meter.

As well as these, vortex meters have also been used. A Coriolis meter is used for low flow ranges. The multivariable transmitter indicated above has to be used with a DP element. In most cases, a wedge is used as a differential element. The operating principles of all these instruments have been discussed in earlier sections in this chapter, and are not repeated here.

1. **Magnetic flow meter:** Magnetic flow meters used for slurry flow depend for their selections on the concentration of solid contents. In some cases special magnetic flow meters meant for slurry applications are used, e.g., Promag 55 of E + H. It has already been pointed out that lining selection depends on the abrasiveness and corrosive characteristics of the slurry. Also, in certain cases, on account of abrasiveness, as in alumina slurry, the noise level is increased. Alumina slurry also covers the electrodes, so, vendors have resorted to different solutions, e.g., ADMAG AXF of YEL uses dual-frequency excitation suitable for both high- and low-frequency meters, for better accuracy of 0.35% and 0.2%, and to combat slurry noise [58]. Transmag of Siemens is designed for mining slurries. Insertion type magnetic flow meters are often used in slurry applications, e.g., ABB, Omega, all have insertion type magnetic flow meters for slurry applications. All these in details have been covered in chapter VII.
2. **Ultrasonic:** Ultrasonic measurement in slurry calls for special setting up of instruments. These instruments are noncontact types, which are easier for installations and retrofitting is possible. Normally these instruments in slurry applications have digital processing and filters to eliminate dirt and noise. These are found in wastewater, oil and gas, limestone slurry, and fly ash slurry applications, e.g., SFM6.1 of Greyline.
3. **Wedge meter:** This is a type of flow element meant for slurry and highly viscous applications. They are used in conjunction with differential pressure/multivariable transmitters. There are not many primary element options, e.g., the Pitot tube is ruled out because of clogging. The orifice plate also has a similar problem and there is also a threat of erosion of the orifice plate [59]. The wedge element is a natural choice in slurry flow measurement by DP. It offers a good turndown ratio of 10:1 and has a calibrated accuracy of up to 0.5% FSD. Normally it calls for higher straight length requirements and moderate unrecoverable pressure loss. However, on account of its ability to measure flow in both directions, no moving parts, and ability to withstand high viscosity

and liquids with suspended solids, it is common in slurry flow measurement.

4. **Elbow:** In many wastewater and civil engineering applications dealing with sewage, elbows are used as differential pressure-producing elements. The remaining measurements are DP measurements. Functioning of elbows was discussed earlier.
5. **Multivariable transmitter/DP transmitter:** From the discussion on flow elements it is clear that primary flow elements are used to create differential pressure, which is measured to calculate flow with the help of differential pressure transmitters. The differential pressure transmitter measures the DP created by the primary flow element. In certain cases, as already discussed in Section 2.1.9, pressure/temperature compensations are necessary, e.g., for alumina slurry flow measurements. In such cases it is necessary to measure the temperature of the stream for compensation. There are multivariable process transmitters which have these are built in. All reputed manufacturers have multivariable transmitters (MVT) in their product range, so, instead of separate temperature compensation, MVTs can be used. DP transmitters and MVTs are discussed in Chapter XI.

The discussions on slurry and complex fluid flow-measuring principles have been briefly described here, but for further discussions Chapter VII may be referenced. Like slurry flow measurement, multiphase flow measurement is also very critical, as discussed in subsequent Section 3.4.0.

3.4.0 Multiphase Flow Measurement Types and Principles

Multiphase flow denotes the simultaneous flow of two or more physically distinct and immiscible substances normally encountered in several engineering applications, namely chemical engineering and crude oil exploration and processing. etc. The main objective of multiphase flow metering (MFM) is to determine precisely the flow rate of the individual constituents. In the case of multiphase systems there are constituents such as gas, petroleum oil, and water (as in the case of a well head in oil exploration), MFM is used to find the gas, petroleum oil, and water. Without separation it is very difficult to get individual flow rates of gas, petroleum oil, and water, thus in MFM a number of devices are be combined in an instrumentation package [60] to calculate precise individual flow rates of the constituents from the combined reading. Depending on the operating conditions, the stream may be homogeneous or nonhomogeneous. If the upstream is homogeneous then three sets of instruments will do and each will measure one characteristic of the mixed flow [60] to get a specific flow rate. If the flow is nonhomogeneous then each constituent velocity and concentration needs to be determined. Accuracy is ensured when the densities (ρ) of the constituents are known (to get the mass flow rate). Another issue to be remembered is that single-phase metering systems provide high-performance measurements of hydrocarbon production [61]. In view of the above, an obvious question arises: *Why go for multiphase measurement at all?* There are reasons for this. With the help of MFM, it is possible to carry out measurement near the well head in the case of oil exploration where MFM is used extensively. Also with the help of MFM, the cost of a test separator can be eliminated. However, on account of uncertainty in multiphase metering, feasibility studies and cost–benefit analyses over a full lifecycle are often carried out before opting for any of the alternatives best suited for the application in the long run. The uncertainty in measurement mainly comes from the complex nature of multiphase flow, in comparison to that in single-phase/constituent flow. However, with modern technologies like magnetic resonance and tomography techniques it is possible to improve the performance of measurement systems. As discussed earlier, multiphase flow is a very complex phenomenon, so, common single-phase characteristics such as velocity profile, turbulence, and boundary layer discussed at the beginning of this chapter are not appropriate for multiphase

flow metering. For these reasons, MFM systems normally require necessary auxiliaries for calibration [61]. Other related technical terms are defined in Chapter IX. The flow structures are classified in flow regimes, which depend on a number of related parameters. Also, there will be variations in the distribution of the fluid phases in space and time for various flow regimes. Flow regimes are also highly dependent on operating conditions. Keeping all these basic points in mind the various approaches that could be adapted for MFM are now described.

3.4.1 APPROACHES FOR MULTIPHASE FLOW METERING

There could be basically two main approaches towards multiphase flow metering, as shown in Fig. I/3.4.1-1. One is a model-based/mathematical

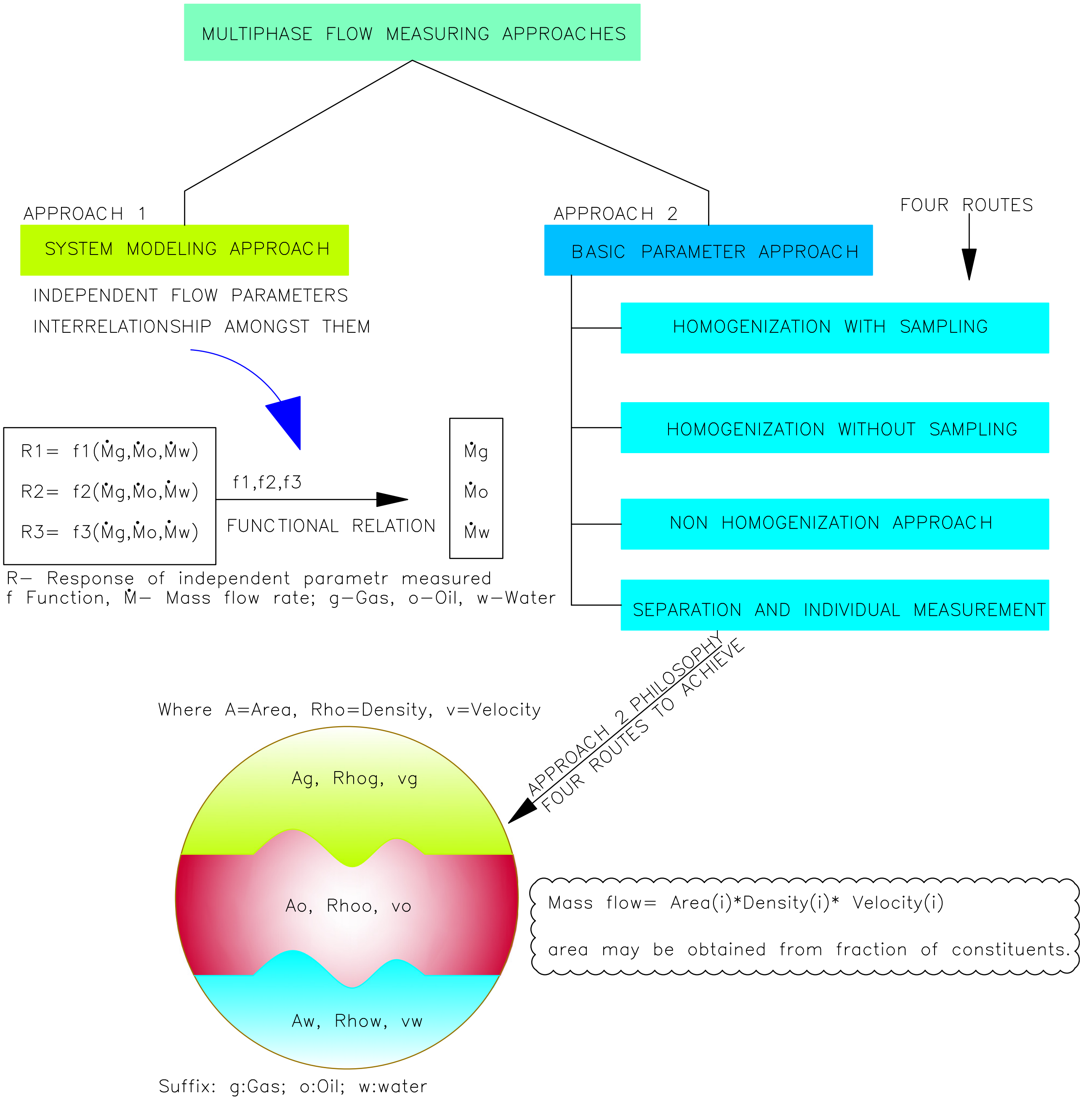


FIGURE I/3.4.1-1 Multiphase flow measurement approaches.

approach and the other is based on determination of the phase velocity and associated parameter approach, i.e., a basic parametric approach. During these discussions in general *three* phases are considered.

1. **Model-based:** This is basically a mathematical approach. For one multiphase system three phases, e.g., gas, oil, and water, and three independent parameters (functions of three individual phase flow rates) are chosen. Let these be R_1, R_2, and R_3 responses of independent parameters referred to above, such that

$$R_1 = f_1\left(\dot{M}g,\ \dot{M}o,\ \dot{M}w\right);$$

$$R_2 = f_2\left(\dot{M}g,\ \dot{M}o,\ \dot{M}w\right)\&$$

$$R_3 = f_3\left(\dot{M}g,\ \dot{M}o,\ \dot{M}w\right)$$

   The relationship of individual mass flow rate and these aforesaid parameters now need to be established. A typical such relationship is depicted in Fig. I/3.4.1-1. However, such a relationship cannot be predicted theoretically, instead this is done with the help of calibration [60]. Another important issue is that calibrating the instrument over the full flow regime is not an easy task, a neural network is often used for this [60].
2. **Basic parameter approach:** With reference to Fig. I/3.4.1-1 it can be seen that if the area pertinent to gas, oil, and water is known, along with the respective densities, then it is possible to compute individual flows by knowing the related velocity. In other words, if there are five parameters, such as three individual constituent velocities and two phase fractions (phase area fractions are defined in Chapter IX), then the individual flows can be computed. As shown in Fig. I/3.4.1-1 there are four major routes by which this can be achieved, i.e., these parameters can be arrived at. In the case of a homogenization system, all phases will have the same velocity, so by knowing the velocity and two phase area fractions, individual flow can be arrived at. Another method is sampling, where representative flow conditions are used to find the phase area fraction and this is combined with the velocity measurement to get the phase flow rate. Also, separation methods are of two types, one full separation and the other partial separation, when excess gas is separated from the main multiphase stream, before phase flow determination. Wet gas measurement, discussed later, is used for phase flow determination.

3.4.2 TYPES OF METERING PHILOSOPHIES

In continuation with the above discussions, the metering can be categorized as:

- in-line meter;
- separation method;
- sampling method;
- wet gas measurement.

Here a wet gas meter has been shown separately as it can be used in various applications and hence has separate significance. Also in this section, various meter types will be discussed to show that in an instrument package different types of instruments may be combined to complete the flow measurement. In this part only very brief principles are discussed; for further details Chapter IX may be referenced. Selected MFM philosophies have been depicted in Fig. I/3.4.2-1.

1. **Inline measurement:** In this category of measurement of the individual phase fractions and total flow or individual phase flow rates are performed directly without requiring any sampling or separation. From discussions in Subsection 3.4.1.2 it can be seen that if the phase area fraction (total area of given pipe) and phase velocity are known then the volume flow of each phase can be established. If the associated density is known the mass flow rate of the individual phase can be computed. Therefore three velocities and at least two phase area fractions need to be established.

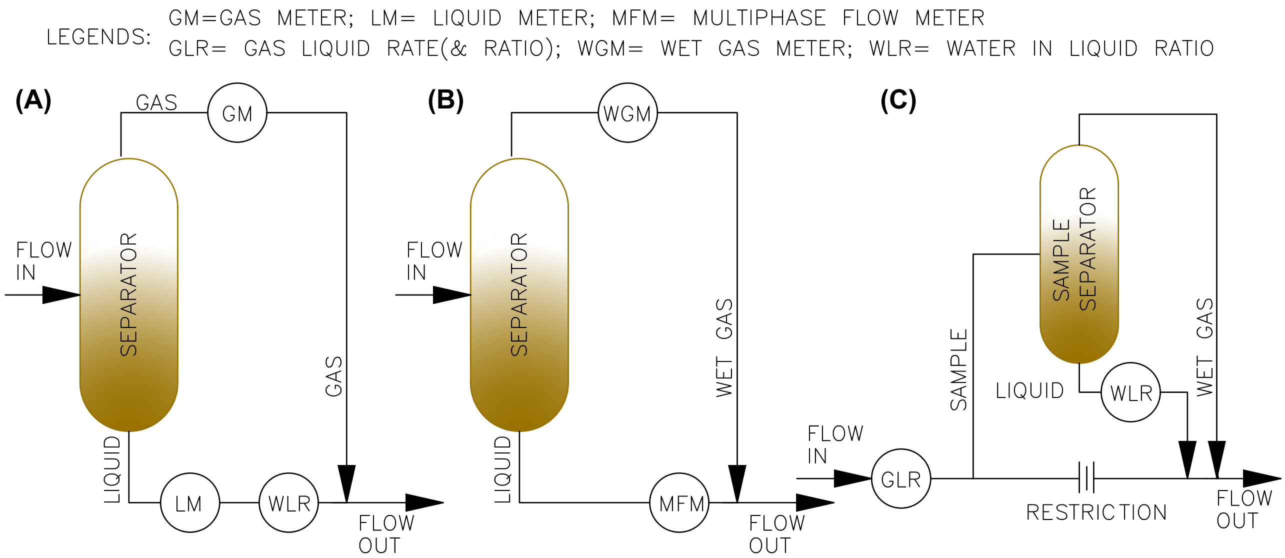


FIGURE I/3.4.2-1 Selected MFM philosophies. (A) Full separation. (B) Partial separation. (C) Sampling.

In order to reduce the number of measurements, it is assumed that two phases of multiphase are of the same velocity. If such an assumption is made, then the system should be properly calibrated and a correction factor or mixer used. To do this two or more of the following categories of instruments are to be deployed. In this method three meters for velocity and at least two meters for phase area fraction are necessary.

2. **Separation method:** The separation type is also considered under MPFs [61]. Separations may be part or full. However, the conventional full separation (when each phase is separated and measured individually) method is not MFM in its true sense. However, the full separation method described below, where gas is separated, falls under MFM. Any separation method is followed by measurement of each of the three phases. The test separators are used for a separation system, where three phases are separated to carry out flow measurements of the velocity of each phase. This means that a minimum of five parameters have to be measured or estimated.
   - *Full separation:* As discussed above, in the full separation method as shown in Fig. I/3.4.2-1A, gas is separated and then the gas flow is measured. The remaining part (i.e., oil + water), total oil + water flow and ratio of water in liquid (WLR) is measured to ascertain each phase flow. Therefore, a gas meter, multiphase flow meter, and water in liquid ratio meter are used. For further details Chapter IX may be referenced.
   - *Partial separation:* In this type of measurement, as shown in Fig. I/3.4.2-1B, only a part of the gas in the multiphase flow is separated. There will therefore be an auxiliary loop around the main loop. With partial separation one can expect some liquid to travel with the gas through the secondary measurement loop [61] and so a wet gas meter is installed to measure the wet gas. The remaining stream will then have less gas volume fraction (GVF) to be measured by a standard meter for MFM. Both wet gas meters and multiphase meters are therefore used.
3. **Sampling method:** This type of metering is very similar to the partial separation method discussed above. In this method separation is not performed on the total multiphase flow, but on a bypassed sample flow which should be representative, as shown in Fig. I/3.4.2-1C. The sample flow is separated into gas and

liquid flow. Measurements as discussed under partial separation are applied (i.e., gas flow is measured *along with* total liquid flow and water in liquid ratio). The total gas/liquid flow rate and ratio are measured in GLR, which is basically a two-phase flow meter. Assuming the bypassed sample flow is representative of the main flow, one can get the following data from GLR:total gas flow, total liquid flow, and gas:liquid ratio. Again, from WLR, one gets the water in liquid ratio. Thus combining the two sets of data from GLR and WLR, one can compute the individual component flow rate. Therefore are sample line gas meters, WLR, and GLR are used. Chapter IX provides further details.

4. **Wet gas meter:** Since wet gas meters have a number of applications they are discussed separately. The discussion starts with a question: *What is wet gas?* Even though this question is very straightforward, the reply is not that straightforward. In loose terms, wet gas is conceived as a gas with little liquid content. How is the term little quantified here? There is no quantitative definition of a wet gas, the mostly widely accepted term is "humid gas" (i.e., gas saturated with liquid vapor) to multiphase flows with a gas volume fraction (volume of gas to the total volume of gas + liquid) of 90% or higher [62]. Wet gas has several applications as listed below [61].
   - Measurement of gas with some entrained liquid for correction to get actual gas measurement;
   - Measurement of hydrocarbon gas and liquid and the liquid needs to be measured;
   - Measurement of hydrocarbon gas, hydrocarbon liquid, and water. The need is to measure hydrocarbons;
   - Measurement of water and small changes of water fraction;
   - Measurement of water salinity or changes in water salinity—well monitoring.

   A wet gas flow meter can be installed with partial separation discussed above or it can be used as a standalone—meaning that this can also be an alternative design of MFM [63]. Wet gas can be measured using various techniques. Based on the Lockhart–Martinelli number (LMN) defined in Fig. I/3.4.2.4-1, wet-gas meters can be classified as **type I** ($LMN \le 0.02$), **type II** ($0.02 < LMN < 0.3$), or **type III** ($LMN > 0.3$) [63]. This means that it depends on the liquid content. Such a classification is not unique, some are classified based on the gas volume fraction (GVF). According to this method (Schlumberger, 2010) there are **type I** (*GVF 98%–100%*), **type II** (*GVF 95%–98%*), and **type III** (*GVF 90%–95%*) with **GVF < 90 for MFM**. In this classification, MFM is distinctly different from wet gas. However, for all practical purposes, MFMs are often used for type III also (as in the first classification). Wet gas meters can be single/two/three-phase meters. When single-phase meters are used for wet gas flow measurements, some corrections are necessary to compensate for the presence of liquid. There are quite good numbers of such correction factors to be applied judiciously. The expected

Lockhart –Martinelli number (LMN) is a dimensionless number used for two phase flow calculations. It basically expresses the fraction of liquid in a fluid flow. Often this is used as a basis for classification of Wet-gas meters.

$$\text{LMN} = \frac{\text{Liquid volume flow rate}}{\text{Gas volume flow rate}}\sqrt{\frac{\text{Liquid density}}{\text{gas density}}} \quad \text{(I/3.4.2.4-1)}$$

FIGURE I/3.4.2.4-1 Lockhart Martinelli number.

liquid and gas flow rates/profiles and requirements for formation water detection, etc. are the basis for meter selections.

3.4.3 MFM TECHNOLOGIES

In the above subsection various philosophies behind MFM have been discussed. In this section discussions will be on various technological principles that are deployed for these measurements. From the discussions below it will be clear that the majority of these techniques are based on single-phase measuring techniques discussed earlier in this chapter and hence they are not repeated here. However, there will be a few techniques, like magnetic resonance, computer tomography, etc., which are not covered earlier in the chapter, and so these are described separately here. Also there are many commonalities in techniques amongst the various philosophies of metering—these have been made clear in Table I/3.4.3-1. Available techniques which can be adapted include but are not limited to:

- Coriolis;
- cross-correlation;
- DP type;
- electrical impedance;
- gamma ray;
- microwave;
- neuron interrogation;
- PD meter;
- turbine;
- ultrasonic;
- vibrating tube;
- vortex;
- weighing;
- tomography.

Here the electrical impedance method refers to electrical impedance tomography (EIT). The electrical impedance method may include, for detection, principles based on conductivity (electrical resistance tomography—ERT)/capacitance (electrical capacitance tomography)/permeability (electromagnetic tomography—EMT), etc. All these have been classified in the following table.

1. **Magnetic resonant MFM:** Magnetic resonant imaging (MRI) is where the resonance of hydrogen nuclei under the influence of a strong magnetic field and RF signal is exploited to detect the hydrogen concentration. Hydrogen is present in gas/oil/water and hence can be used to reveal the phase fraction (also velocity). Based on this technology—developed by Krohne in collaboration with Shell—gets rid of radioactive materials as well as not having any moving parts. As shown in Fig. I/3.4.3.1-1, there are several sections to this meter. The instrument was developed from magnetic resonance, which is commonly used in medical systems. When a hydrogen nucleus is subjected to a strong magnetic field there will be a precession of hydrogen protons around the magnetic field at a frequency proportional to the magnetic field strength denoted by B. When this interacts with radio frequency (RF) waves of the same frequency it starts to resonate. The protons absorb and reemit the radio energy of the same frequency. There is then the formation of an echo which is referred to as the Hahn echo, as explained in Section 3.7.1 of Chapter IX. This echo decays following convective decay as the flow is passed out of an RF coil. This convective decay gives the liquid velocity. There is an important property of oil and water, exploited in the MR multiphase flow meter, which is the difference in longitudinal relaxation time, T_1 [64]. So, in the premagnetization area, WLR is determined from which the velocity of water and oil is determined. Gas velocity is determined by MR imaging. A system based on nuclear magnetic resonance (NMR) is in the development stage but has limitations such as being complex to comprehend, expensive, and with poor temporal resolution (hence in velocity measurement range) [65]. This meter is further discussed in Chapter IX where details on operating principle has been defined.
2. **Tomography and gamma ray detection:** Tomography may be referred to as a method of producing a 2D/3D image of the internal

TABLE I/3.4.3-1 Multiphase Flow Metering Technologies and Use

Philosophy →	**In Line MFM (Any of >2 Techniques)**	**Separation Method**			**Wet Gas**			
Technology ↓		**Full**	**Partial**	**Sampling**	**Type I**	**Type II**	**Type III (MFM)**	**Remarks**
Coriolis		Gas flow: Type I WG	Covered in Type I WG and MFM	Gas flow: Type I WG	Yes			
Cross-correlation	Yes (velocity)						Yes (MFM)	
DP type Venturi/ orifice/V-cone	Yes (all)				Yes (all)	Dual DP/ Venturi* Venturi**	Yes (MFM)	*with tracer **with vortex
Electrical impedance[a]	Yes (both)	Yes (WLR)		Yes (WLR)				
Gamma ray	Yes			Yes (GLR)				
Microwave	Yes							
Neutron Interrogation	Yes			Yes (GLR)			Yes (MFM)	
PD meter	Yes						Yes (MFM)	
Turbine					Yes		Yes (MFM)	
Ultrasonic	Yes				Yes			
Vibrating tube		Yes (WLR)		Yes (WLR) (GLR)				
Vortex					Yes	Yes*		*+ Venturi
Weighing				Yes (GLR)				

GLR, gas liquid ratio; *WG*, wet-gas; *WLR*, water in liquid ratio.
[a]*Electrical impedance: may be conductivity or capacitance.*

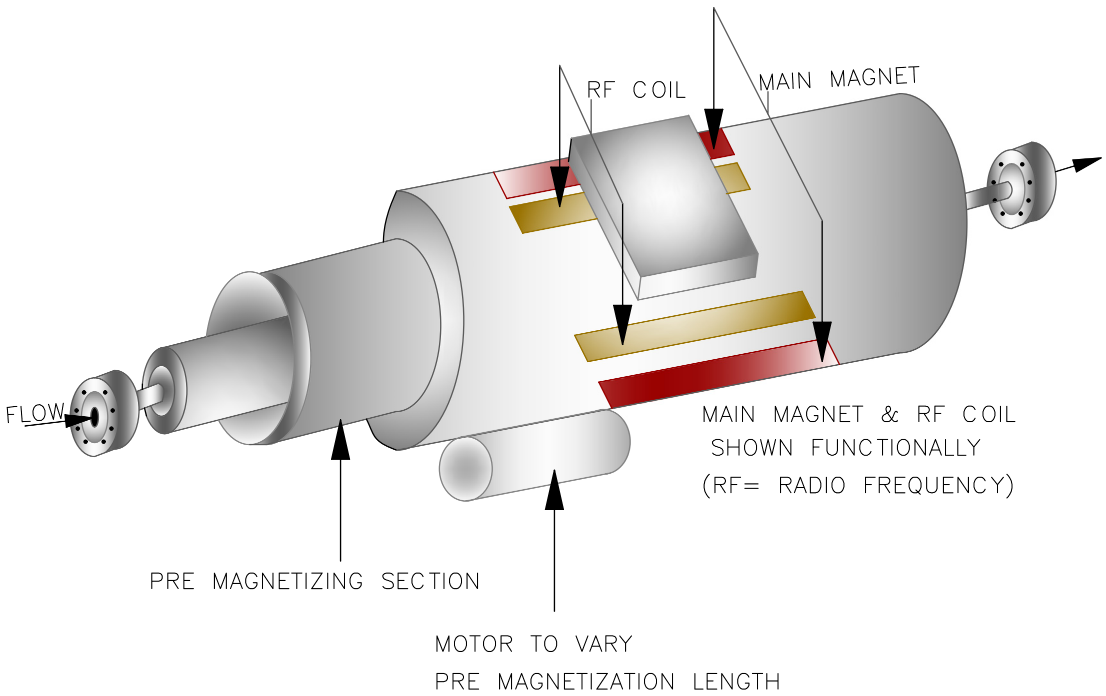


FIGURE I/3.4.3.1-1 MFM magnetic resonance. *Based on an idea from a Krohne document.*

structures of a solid object by the passage of waves of energy penetrating through those structures. Industrial process tomography (IPT) refers to cross-sectional imaging of parameters of industrial processes. These are normally functions of time. There are a large number of IPT measurement principles the have been developed (or are still under development) with electrical impedance methods (conductivity, such as the measurement of capacitance, permittivity); radiation-based methods ranging from infrared, microwave, X-rays, gamma-rays, and even NMR, ultrasound and acoustic methods, to mention a few. Of so many choices one has to be selected with a sensing method compatible to the process. There is also a question of speed of response, matter (e.g., density), and spatial resolution [66]. The most common tomography methods are gamma ray tomography and X-ray tomography, which are sensitive to the density or the atomic composition of the process medium (depending on energy level). Hard-field and soft-field are two categories of sensor systems. In hard-field systems the sensitivity does not change with position or distribution of the parameter in measurement volume, namely the gamma system. In soft-field systems sensitivity is dependent on the position of the measurement volume and the distribution of the parameter in the measurement volume, i.e., the capacitance system. Tomography in industrial measurement is built around a combination of one or several radiation sources—radiation detectors. Important system parameters are then derived from the measurement of interactions between the ionizing radiation, etc. There are scattering and X-ray techniques in tomography also, but mostly from low-response intensity [66]. As mentioned earlier, tracing is done with the help of radioisotopes. Tracing is a powerful tool used for measurement of flow rate and residence time and for leakage detection.

- *Dual-energy gamma detection:* This is also a kind of tomography, where dual-energy systems are used. In dual-energy gamma detection, energy-sensitive detectors are

used. The highest energy attenuation occurs due to Compton scattering (Compton scattering occurs due to the *interaction of the X-ray or gamma photon with the outermost valence electron* at the atomic level). The linear attenuation coefficients of the components are proportional to their densities. In the lowest energy (dominated by photoelectric absorption), the linear attenuation coefficients are strongly dependent on the effective atomic number or composition. As a result of this, two independent measurements can be made, for determination of the volumetric fractions of three components. This principle was originally developed for gas/oil/water measurements, and later also for ash in coal measurements [66]. The process density and atomic composition may also be measured by the dual-modality principle using one low-radiation energy system. A dual-modality system based on scatter and annihilation radiation for measurement of ash in coal has also been developed [66].

- *System design fundamentals:* For applying (gamma-ray) tomography in industry it is extremely important to identify the basic process parameters and the properties for which the study needs to be undertaken. These are important because most often the process properties are the deciding factor for the system requirements. The most important of these properties include but are not limited to the following.
  - Size or diameter of the system;
  - Densities, composition of different materials present in the system;
  - Vessel/pipe wall type/thickness/form; bandwidth of the phenomena to be studied;
  - Environmental conditions: temperature, humidity, dust, location, hazardous atmosphere, etc.
- *Basic tomography principles:* For radiation tomography a set of source(s) and detector(s) are necessary. Source(s) and detector(s) are placed on opposite sides of the object/process. Collimated beams are obtained along several paths from many directions around the object to cover the cross-section uniformly. The sources could be gamma or X-rays, but here mainly gamma rays are considered. When beam radiations traverse a single path through a process/object, it is attenuated primarily due to absorption (part scattering). In computed tomography the aim is to discover the extent to which the material in each element attenuates the beam.

As shown in Fig. I/3.4.3.2-1, in all cases except tracers (where the source is not shielded) both the source and detectors have a shield for safety reasons. There are various methods: narrow beam/wide beam detection or detection due to scattering. These are elaborated in Fig. I/3.4.3.2-1A. As shown in Fig. I/3.4.3.2-1B, there are various methods of scanning to obtain the process information. It is also possible to get instant tomography as shown in Fig. I/3.4.3.2-1B4. As discussed earlier, there are other tomography methods such as EIT. Depending on the measuring principles, EIT could be electrical resistance tomography (ERT), electrical capacitance tomography (ECT), or electromagnetic tomography (EMT). In these methods, electrical conductivity, permittivity, and permeability properties are exploited, respectively. These are covered in Chapter IX. The discussions on flow-measuring principles are now complete and we now see how to select the meter best suited for a particular application.

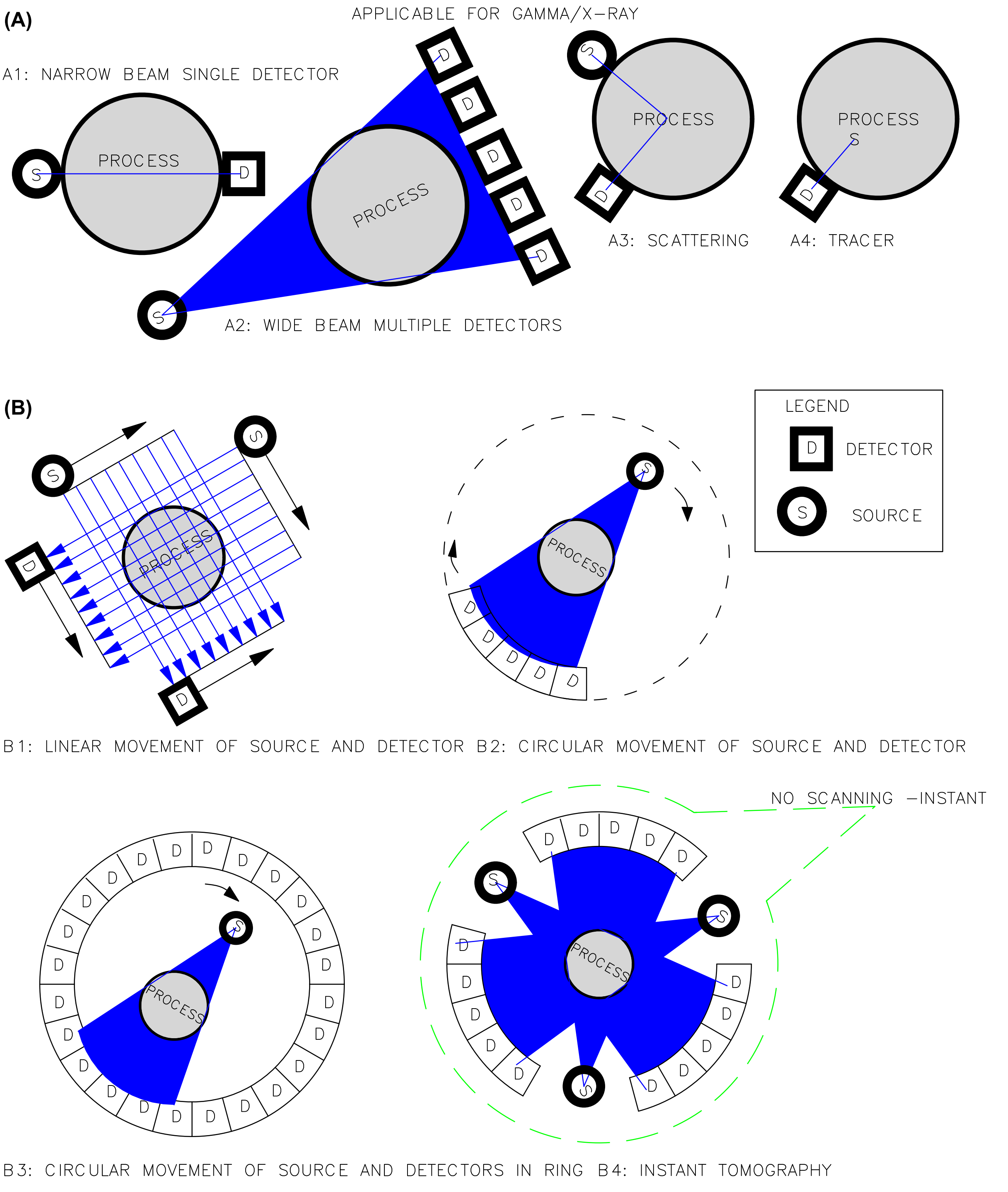


FIGURE I/3.4.3.2-1 Radiation tomography. (A) Radiation tomography in various modes. (B) Scanning and instant tomography.

4.0.0 SELECTION OF FLOW METERS

After reading Section 3.0.0, it is possible to become confused regarding the selection of a flow meter for a particular application. In this connection readers need to note that in the above section, only those flow meters which are popular in industries have been discussed. There are quite a good number of other flow meters (of which, most fall under one of the categories discussed) that may be of slightly different or may be used in different applications. Therefore, with the countless numbers and types of flow meters currently available in the market, making the selection of an appropriate flow meter is often a daunting task for a designer. However, in certain applications this choice, or elimination of options, may not be that difficult. This will be clear from the following example: a Coriolis mass flow meter is a good choice for custody transfer applications. Similarly, in cases where the flowing medium does not have good electrical conductivity (hydrocarbon oil, e.g., heavy fuel oil) the choice of an electromagnetic flow meter can easily be eliminated. Similarly for laminar flow, a head type flow meter with DP transmitter may be eliminated. There may be a natural conflict arising from the cost and capability of the flow meter. These two issues need to be properly balanced. Prior to detailed discussions on the selection procedure, it is better to have a short survey to see *why* the proper selection procedure is so important from the following discussions in a generalized form.

1. **Flow meter needs:** There are many applications, such as lube oil flow in a large drive for bearing lubrication, where there is a need to ensure that there is a flow of lube oil in the required pipe. In such applications there is no real need to use a sophisticated flow meter. A simple flow/no flow switch will do. There are some other types of application, e.g., a balance leak off flow in a boiler feed pump (BFP), where one needs to ensure that flow in the line is above a set point, in such case the demand can be fulfilled by a flow switch (e.g., a target flow switch). Many applications, such as fluid flow through filters, cooling systems, small pumps, and intake outlets and/or lube oils for turbine bearings to name a few, have users often wanting to know the flow rate in the pipeline. In such cases, a simple flow indicator can be deployed at a fraction of the cost of the standard electronic flow meter. These are very easy to install and do not require external power but they meet the requirements. Apart from these, there are certain applications in industrial plants where a rough estimation of flow will do, e.g., where 5%−10% accuracy will suffice. In such installations, feature bends or joints can be readily converted into a crude flow meter with the help a DPT or elbow meter. When calibration is properly done such a simple flow meter can achieve 5% accuracy [67]. In certain applications such as those in nuclear power plant or in a semiconductor manufacturing unit high precision flow measurement is the need of the application. Therefore, before deciding the requirements for a sophisticated flow meter one should make a prefeasibility study.
2. **Initial cost:** Though unfortunate, it has been found that there is a tendency of project people to consider the initial cost as a primary criterion for selection. Lifecycle costs, which would include installation cost, calibration and testing cost, and maintenance, are often put in as low priority—even neglected at times.
3. **High accuracy:** From experience it has also been found that some people have the peculiar tendency of selecting the meters based on higher accuracy and product specification. Let us take an example. For measurement of water flow in an ordinary water line in a remote location, a turbine flow meter was opted for in place of an orifice plate and DP transmitter. The reason cited was that the combined accuracy of an orifice plate and DP transmitter would be higher than a turbine meter. Since turbine meters have moving parts and turbine meters require regular maintenance, after a couple of years the customer reported nonfunctioning of the same. This example is given here

to show that it is not the accuracy alone which should decide the selection.

4. **Organizational standards:** Sometimes organizations have peculiar standards, e.g., one company has a standard that requires putting a magnetic flow meter in the water line. Such a broad-based standard at times makes the system problematic, e.g. putting a magnetic flow meter in a large circulating pipe (in their captive power plant) or in demineralized water may be impractical propositions. Also, it is not unlikely that selecting the highest accuracy meter based on product specifications often results in the lowest measurement accuracy in the actual applications [68].
5. **Product specification:** Another issue is where someone relies too heavily on product specification from the vendor. There are quite a good numbers of issues one needs to address for meter selection. Some of these are listed here.
    - *Application:* Without understanding the flow problem, if one decides only on basis of product specification, the result could be catastrophic, resulting in a very high process time. When one goes through product specification of turbine flow meters and magnetic flow meters both offer very good accuracies and wide application ranges. Now, if someone selects a magnetic flow meter for heavy oil application and contaminated and abrasive liquid, respectively, then one can easily understand that the system will not work and there will be high process downtime.
    - *Proven product:* There are many vendors who come out with good specifications with the latest technologies which at times may appeal to the designer. Here the question is whether the technology is proven for the applications in question, and post-procurement support needs to be considered.
    - *Plant-specific issues:* Every plant or application may have its own specific problem or issue associated with the application, which might not be clear from the product specification and product guide but be felt or realized by the designer (through proper understanding of measurement) while making the selection, e.g., in a particular application it is not possible to have sufficient straight length or low flow in a horizontal line. In these cases the designer needs to consider the flow meters that have a lower straight length requirement. For the second case, the designer should try to find a vertical loop/reducer so as to ensure the flow meter is full at all the times.
6. **Rate or totalized flow:** We now change our focus to another important issue. In a power plant people are very much interested to know and compare the feed water flow rate with the steam flow rate, i.e., they are more interested in flow rate measurements for boiler control. On the other hand, for domestic flow meters and/or discharges through an open channel, people are more interested in knowing the total flow over a set time than the flow rate. So, for flow meter selection there should be a clear understanding of the requirements of the particular application.
7. **Technical parameter for meter selection:** Every fluid or solid behaves differently while flowing in a closed pipe.
    - *Fluid flow:* In the case of fluid flow this is dependent mainly on the flow profile viscosity, which in turn affects velocity. Again, from the previous discussions (Subsection 1.1.2.5), it has been seen that the flow profile changes based on whether it is Newtonian (e.g., water) or non-Newtonian (e.g., paint) fluid. For Newtonian fluids, there is a (proportional) relationship between flow and shear force. In contrast, for non-Newtonian fluids no such relationship exists, instead the flow of these fluids has variations, with viscosity changing either with time or due to increased resistance arising out of the collision of two different velocities. So, for selection of the best fluid flow meter the Reynolds number plays a significant role.

- *Solid flow:* The majority of solid flow meters depend on weighing in some form or another. However, there are ways and means, as already indicated earlier in Section 3.2.0, for measurement of solid flow. The conditions and properties of the flowing solids have a major impact on the type of flow meter required. In the case of solid flow measurement prefeeding equipment is very important. In the case of solid flow meters parameters like material density/bulk density, material characteristics (e.g., sulfur which gets compacted very quickly), flow rate, temperature, moisture content, particle size, installation space, prefeed device, and material compatibility play major roles. Another important issue here is that flow meter discharge also varies with material characteristics and the amount of flow. Hazardous approval is also very important in certain applications.

8. **Thorough study:** From the discussions put forward above it is clear that any flow meter selection based on any single criterion is neither possible nor recommended. Therefore, time should be invested in fully evaluating the nature of the process medium and of the overall installation [1]. Having discussed all these, an interesting fact from a report is presented to show that at times *old is gold.* According to ARC Advisory Group's "Flow meter Worldwide Market Outlook" report, differential pressure transmitters still account for nearly half of all flow meters shipped each year even after proliferation of new flow metering technologies. Intelligent multivariable pressure transmitters have added new life to this mature, but obviously still viable, technology [68].

   The discussions presented above may be considered as a preamble to form the basis of discussions which were necessary to bring major issues before reader for focusing on selection process. With this the preamble on meter selection is concluded and we focus directly on the selection process.

4.1.0 General Discussions on the Flow Meter Selection Process (Closed Pipe)

From the above discussions it has been found that there are a number of criteria which need to be studied thoroughly for selection of a flow meter for a particular application. Although a detailed and thorough study is necessary, it is not that cumbersome a process. In real life, in the majority of industries for various flow measurements, the types of flow meters are well established through their performance in the industry. This will be clear from some examples: For high-pressure steam flow measurements flow nozzles with DPTs are well proven. Also, for pressure–temperature compensation, instead of DPTs, PTs and multivariable transmitters (MVTs) can be used. This is not really a flow meter selection process, because the same head type measurement is retained. Things would be different if the head type measurement was to be replaced by a swirl meter or if a target flow meter in heavy fuel oil flow measurement was to be replaced by a mass flow meter. In all these cases the pertinent questions are *reason for changes*, cost, track record of the same in a similar application, requirements of straight length, permanent pressure drop, etc. In such cases prior to proposing the change, especially when there is the probability of a cost increase, one has to have proper grounds to convince management and show results. In order to do this, as discussed earlier, one must have a thorough knowledge of the issue. From experience, literature studies, and case studies it has been found that such selection is a process which can be modeled, as shown in Fig. I/4.1.0-1.

With the objective and purpose of flow measurement the designer is able to focus on relevant selection criteria and to prioritize various relevant factors. Designer can decide whether it is for local indication and/or needs remote transmission capability. The designer needs to know whether the purpose is for monitoring only, monitoring and control, or if any safety-related issues are to be considered. The various flow metering technologies are best suited for certain indications,

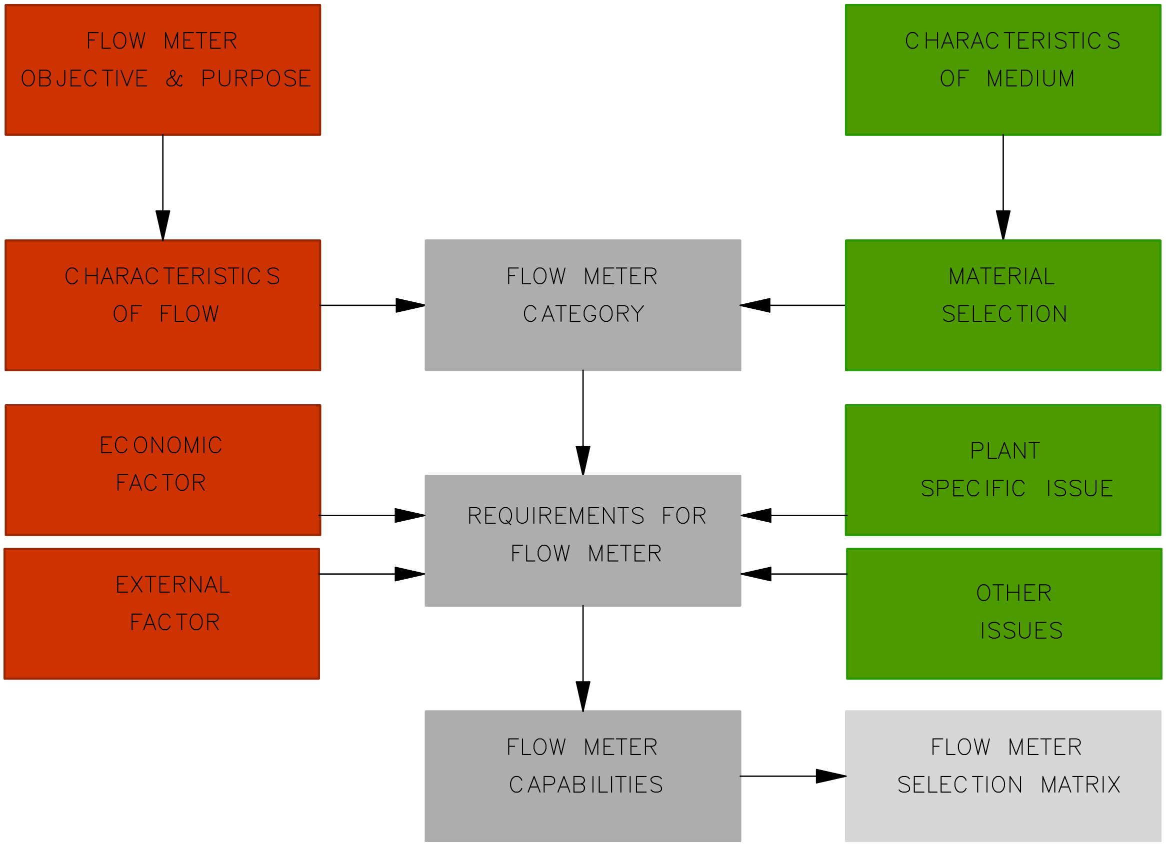


FIGURE I/4.1.0-1 Flow meter selection model.

e.g., the swirl flow meter is more suitable for steam flow (and there is no need to concentrate on a magnetic flow meter). Flow characteristics indicate the flow range pipe size, and whether the rate flow or totalized flow is important. As the name signifies, medium characteristics indicate fluid characteristics such as liquid/gas/steam/slurry/multiphase or solid. It provides the operating conditions. It also indicates the quality of the fluid, such as clean/dirty and if it has corrosive/erosive properties. It also indicates viscosity effects, Reynolds number, etc. and in the case of solid flow it indicates the material density and properties such as moisture content, size, flowability for power fluid, and/or compactness characteristics, etc. From these basic material selection and basic meter categories can be assessed. After flow and medium characteristics are ascertained another round of evaluation with respect to various other factors takes place. There are certain plant-specific issues, including installation issues like space availability, straight length requirements, etc. This shall also include whether an inline meter or probe type meters are suitable. There could be some other issues, e.g., safety issues when radioactive materials are involved, availability of power source, interference, display types, communication/networking/configuring issues. Economic factors obviously address the lifecycle cost, which involves initial cost, installation, testing, calibration, and maintenance costs, which often could be as high as 65% of the material cost. The quantification of cost for each of the choices is done to make an objective decision by assessing the economic impact [67]. Environmental condition, enclosure type (IP class), and hazardous area classification have issues related to explosion-proof enclosures

or intrinsic safety issues falling under external factors. All these together make the flow meter requirements. From these, the relevant flow meter categories are decided to check the capability. Since under the flow meter category there could be more than one selection, the final selection is done with the help of a flow meter selection matrix (discussed later in this chapter) where various flow meter categories are compared and one needs to select the best one suitable for the application, taking into account all the criteria involved. One important point here for the designer is that the purchase specifications need to be specified in terms of functional and plant-specific requirements so that a large number of vendors can participate. This will help not only with good competition but also means the best one can be chosen. Unfortunately at times some overenthusiastic designers mention too many vendor-specific data which may be the best of category from a flow meter angle but may not be suitable for the application, e.g., the specification may call for more than two/three fieldbus when these are not called for in that particular application. This ultimately may reduce the accuracy of the specification. Having discussed all these, it is better to divide the entire issue in suitable areas and discuss the issues point by point, before the so-called selection matrix. Presented below are brief typical lists of criteria normally considered for flow meter selection.

1. **Process media/fluid characteristics:**
   - Measuring media property;
   - Solid content;
   - Gas content in liquid;
   - Viscosity effect;
   - Reynolds number;
   - Corrosion;
   - Flow range/turn down ratio.
2. **Design construction:**
   - MOC;
   - Lining;
   - Accessories;
   - Grounding.
3. **Meter Sizing**.
4. **Type of Measurement**.
5. **Flow regime (turbulent, laminar, transition)**.
6. **Flow rate information:**
   - Mass;
   - Volume;
   - Compensation;
   - Output and indication.
7. **Application environment:**
   - Application limit;
   - Other conditions e.g., vibration;
   - Reverse flow.
8. **Performance:**
   - Desired accuracy;
   - Span;
   - Range rangeability;
   - Pressure drop.
9. **Installation and maintenance requirements:**
   - Straight pipe requirements;
   - Mounting.
10. **Cost effect**.
11. **Approval requirement**.

    In the subsequent subsections these will be discussed at length.

4.2.0 Specific Discussions on the Flow Meter Selection Process (Closed Pipe)

From the earlier discussions it has been made clear that detailed and thorough investigation is necessary when selecting a flow meter, especially when it is done for a new application, to see the pros and cons from various points of view which shall include but are not limited to process conditions, meter capability requirement, application issues, cost and approval process. In this section discussions shall be presented on these issues.

4.2.1 PROCESS ISSUES FOR FLOW METER SELECTION

There are a number of process-related issues which dominate flow meter selection, the major issues of which are presented here.

1. **Measuring media properties:** Various flow meters are designed to operate best in different media and under varied operating conditions. So, in the selection process the measuring

medium should be the first criterion. Before the appropriate flow meter can be selected, the type of medium and its properties need to be analyzed. Therefore it is needless to explain the importance of understanding the limitations inherent to each type of flow meter in handling fluids/solids. Therefore flow meters are classified as either liquid/gas or solid meters. In the case of fluid meters the most important difference between liquids and gases/steam lies in their relative compressibility. As a result of this any change to pressure variations will affect the material density in the case of a gas. However, temperature will affect both but more so for gas. Naturally, major issues involved in fluid flow include operating pressure (gas), temperature, allowable pressure drop, density (or specific gravity), conductivity, viscosity (Newtonian or non-Newtonian?), and vapor pressure at maximum operating temperature. Along with these it is important to note how variations of these properties affect their measurement. Also, fluid compositional details, the presence of foreign materials, tendency to coat, and all safety, corrosivity, and toxicity information are important information for meter selection.

2. **Foreign matters:** There could be solids in liquid medium that present as foreign matter. Also, gas or bubbles at times are present in liquid as foreign matter. In both these cases there will be error in readings and their effects need to be suitably taken care of.
   - *Solids in liquid:* The presence of solids in fluid flow is undesirable in almost all cases, except ultrasonic Doppler flow meters, where it is used as a reflective medium. However, in transit time ultrasonic flow meters only a small amount of dust in fluid is allowed. These solids can give rise to a lot of undesirable issues. When dust is present in gas it is dangerous as, in gas flow, velocity is very high so associated dust particles will have higher kinetic energy that can cause damage and deposits. These contaminations are undesirable because they not only form paste and slurry but their effect in flow measurement is unpredictable. These dusts also cause damage to impellers and rotating parts of totalizing flow meters [1]. Dusts/solid particles are very vulnerable to sharp edge of flow elements like orifice plate/variable area flow meters. Vortex and swirl flow meters flush minor contamination through the meter [1]. In the case of magnetic flow meters such solid particles could damage the lining. Additionally any deposits of nonconductive dust on an electrode may make the magnetic flow meter fail to function. Also, conductive deposits can cause reading errors. In the case of a mass flow meter, dust will follow associated vibrations and could affect viscosity and create reading errors. In the case of slurries there will be hydraulic transport of solids causing an increase in abrasion. In such cases, a magnetic flow meter with a special lining (such as ceramic carbide or soft rubber) could be used. Also, in such cases the density is variable as the solid particle contents are variable, so in these instances density measurements need to be carried out with, e.g., radioisotope densitometers. Undesirable deposits of solids must be scraped, so an inline flow meter with matching inside diameter should be chosen [1].
   - *Gas in liquids:* Fluid meters are normally separate and specific for liquids and gas applications, but they cannot distinguish the presence of gas in liquid and so errors result. Even in a Coriolis mass flow meter on account of the damping effect of gas there could be an error in measurement. It is known that the small amount of water in steam is not allowed inside steam turbines as it may cause excess speed. In the same manner, a slight gas content in the liquid in a turbine meter may cause excess speed of the turbine and cause reading errors. Cavitations due to bubbles are a

common phenomenon, especially in vortex meters. Even a small quantity of bubbles may change the reading in transit time ultrasonic flow meters.

3. **Viscosity and Reynolds number:** Viscosity, which is highly connected with the Reynolds number, is extremely important for flow meter selection. Small Reynolds numbers have varying effects, depending on the measuring method [1]. In contrast, for high viscous fluids pressure drop is an important issue. Comparatively, for gas measurements. Mass flow meters also fall under this category but the pressure drop in mass flow metering is indirectly related to viscosity. For highly viscous applications, positive displacement flow meters (like oval gear/oscillating pistons) and target flow meters give good results. In the case of vortex, swirl, and turbine flow meters, an increase in viscosity causes a reduction in the span of measurement. Although viscosity does not affect ultrasonic meters, flow measurements by ultrasonic meters in transition zones are very difficult as they are affected by the Reynolds number.
4. **Solid flow meter selection criteria:** Like any other flow meters for solid flow meters selection criteria can be classified as cost, accuracy, and appropriateness. When cost is not a big issue then many features can be achieved. However for cost constraint some compromise may have to be done. Accuracy is based on demand from the process, therefore selection is a major issue. For this there are a number of variables to be considered, such as material density, flow rate, temperature, moisture content, particle size, material characteristics, installation space, prefeed device, and material compatibility. There are just as many variables to consider, many of which can change over seasons or even with the daily change in weather [43]. Changes to variable properties often affect prefeed devices. In one cement plant in Jordan— normally a dry climate—there was easy flow from the raw material beans. However, during winter, due to the moist climate and/or dew, ice— material flow was affected so vibrators were used. Normally for impact scale, centripetal solid flow meters, and Coriolis solid flow meters gravity flow is recommended rather than pneumatic conveying as these meters do not work well with the latter. Microwave meters are moderate with respect to these feeding systems. Gamma type sensors for pipe flow measurements are used for a vertical line with gravity feeding. In the case of solid flow meters the type selected is based on the space available but more so on the type of prefeed device on/off control means and type of conveying.
5. **Corrosion/erosion:** Frankly speaking, this should be part of Subsection 4.2.1.1, but it is included separately to emphasize the importance of corrosive medium as it is related to material selections. The issue is so important that a minor deviation or wrong selection can result in complete failure of the system. For example, Wrong selection of material for a gasket can result in an inoperative measuring device [1]. On account of elaborated parts and complex design it is very difficult to choose proper materials for meters with volume totalizing. Therefore these are not recommended for corrosive fluids. In the case of head type measurements, flow elements, as well as pipes and fittings, need to be selected to match with the corrosiveness of the medium. Variable area flow meters made of special materials are expensive and, therefore, rarely deployed [1]. It is common practice to coat the electrode and/or probes with coatings that are corrosion-resistant. Also, suitable linings are used in magnetic flow meters to protect them from corrosion. For slurry flows with abrasive materials soft linings are used. In the case that fluids are both abrasive and corrosive ceramic linings are used.
6. **Flow regime:** The flow regime is basically medium flow characteristics based on

Reynolds number. Flow characteristics in conjunction with piping configuration are responsible for variations of flow regimes. The theoretical condition of a flow profile shown in Fig. I/1.2.2-3 will vary with the velocity profile and Reynolds number, but measuring devices have limited capability to cope with that situation. This may result in reading errors. The spans of the indirect volume totalizers, the differential pressure, and variable area flow meters decrease with increasing viscosity [1]. Direct flow totalizing operates accurately with low Reynolds number. Oval gear meters, rotating vanes, oscillating pistons, variable area rotameters, etc. show steady operation in all flow regimes, i.e., laminar, transition, and turbulent. In contrast a swirl/vortex meter is steady only in turbulent flow but not for the other regimes. Coriolis mass flow meters are not much affected by flow regimes. Turbine/thermal mass require steady section in 15D and 5D for inlet outlet respectively for proper operation. Similarly for head type measurements there should not be an effect with variations of flow regime; however they have some steady-state section governed by ISO 5162. In cases of nonsymmetric profiles, large straight lengths are required for the direct flow totalizing devices described earlier. So, in many cases flow straighteners are used to reduce straight length requirements and get steady flow sections.

The focus now moves to flow meter constructional issues.

4.2.2 SELECTION PROCESS RELATED TO THE FLOW METER

For each flow measurement, there are a few expectations regarding the measurements. Similarly, each flow-measuring system or flow meter has certain features and characteristics. In order to get the best results, the flow metering requirements should match the features of the flow meter. It is something like impedance matching for maximum power transfer. When these features exceed the actual requirements, then it is a poor selection in the sense of unnecessary additional expenditure and incorrect/inadequate utilization. In contrast, if the features fall short of requirements then the flow meter will not be suitable. Although it is not possible in reality to totally match all features with requirements, efforts should be made to bring the two things together. From the previous subsection various requirements have been investigated from a process point of view. In this subsection efforts will be seen on how the requirements need to be met by the meter features. Here a few examples have been chosen to show how these can be done prior to moving on to the details. Almost all meters normally offer a number of options for various things, e.g., material of construction of elements and/or meter body (e.g., electromagnetic flow meter) are selected in such a way that meet the requirements, e.g., for a corrosive fluid such as sulfuric acid, one may select HastelloyC for the flow meter wetted parts. As stated earlier, for slurry applications with abrasive solids, lining materials for electromagnetic flow meters may be soft materials. And in some cases accessories like flow straighteners are necessary for better results and to reduce the straight pipe length requirement.

Grounding is also an important issue for electromagnetic flow meters. Grounding of an electromagnetic flow meter as per VDE 01000 is necessary for safety as well as for measurement accuracy. Grounded electrodes are considered from a cost point of view and are not applicable for all meter configurations. It is needless to say that since potential developed is of very low values, any wrong grounding can jeopardize the entire measurement in an electromagnetic flow meter. A single grounding plate is installed for plastic or insulated pipes and used for devices without grounding electrodes. Two grounding plates are installed for insulated pipes to get rid of stray potentials [1].

These issues are now looked at in detail.

1. **Meter sizing and selection:** The need for flow element sizing for head type measurements is well established. Similarly other flow meter

sizes should also be selected according to the operating condition requirements. At times it is necessary to use lower size (than pipe size) meter which may give better performance than a line size meter. However, in that case the effect of reducers needs to be considered. In some applications, one size more than the required meter size (***not*** more than the line size) is selected to cope up with pressure loss. Therefore for meter selections due consideration must also be given to meter sizing.

2. **Material of construction (MOC):** As indicated above, flowing medium corrosivity and abrasiveness is the major criterion for the selection of materials for flow meters with special reference to the parts which are difficult to manufacture. These are guided by the available materials specified by reputed manufacturers. For PD meters, turbine meters, swirl, vortex meters, and mass flow meters MOC is very important. So, while making the selection in favor care must be taken regarding available material lists and their suitability for the application. The orifice plate or the nozzle (along with piping, fittings, and the transmitter sensing part) must be manufactured from corrosion resistant materials. In the case of a flow nozzle in high-pressure steam applications it may be necessary to take the spool piece from the owner to have the flow nozzle fitted into the same. So, good coordination is called for. The price of variable area flow meters in medical applications and those made up from stainless steel is increased due to the materials. They are only installed if no supply power is available at the measuring point. In flow meters, such as electromagnetic flow meters, where there is a lining, the situation can be handled in a better way with a PTFE lining. However, as stated earlier, for slurry applications the selection of the lining is critical and care must be taken to ensure that there is no deposition on the electrodes. Platinum is exceptionally good as an electrode material. The ultrasonic flow meter requires the proper protective tube material for the sound transducer (transmitter/receiver) [1]. Another important issue is grounding (covered above). Now let us look into other aspects of flow meters.
3. **Type of measurement:** As mass is an intrinsic property, in most cases the mass balance is done in industrial processes. In view of the above, it is always better to measure flow in terms of mass flow measurement. However, volume flow measurements are also quite popular in chemical/industrial processes. In the case of solid flow measurements, these are done as mass flow. There are cases when volume flow measurements are done, and mass flow is computed from the density of the fluid. In head type, basically volume flow is measured which after temperature and pressure (for compressible fluid) mass flow is computed. On the other hand, in PD meters, turbine meters, and variable area meters only volume flow is measured and applied for volumetric flow measurement. In these cases the meter cannot properly sense pressure/temperature changes. In contrast Coriolis meters and thermal mass flow meters the principle itself accounts for mass measurement but volume flow can be arrived at by measuring density also. Thermal mass flow meters are virtually insensitive to variations in temperature or pressure [69].
4. **Flow information:** One of the most important issues in meter selection is to decide the application of flow information. In some cases flow rates are important, whereas in some cases totalized flow measurements are vital. For totalizing flow applications some the meters, like those in the PD meter category, are better suited, whereas head type meters and mass flow meters are mainly meant for rate flow but can be used to get totalized flow with the help of a transmitter, flow recorder, and totalizer.
5. **Output types and displays:** During initial discussions it has been mentioned that at times

only local indications are necessary for which a sight flow indicator or rotameter can be deployed. A rotameter with remote transmission is also available. Flow meters with remote transmission also have divisions of analog (reaching obsolescence) or digital transmission. Later calls were made for selection of communication types by HART protocol and/or fieldbus system. There are a number of fieldbus systems as well as safety fieldbus systems. For further details the author's book [70] may be referenced. Another important issue is the display, which could be analog and/or digital. These displays can be flow rate type, or totalized, or both at the local level is possible. In the case of DPTs, displays may be 0%–100% in terms of DP and/or flow. Naturally the question arises whether DPT outputs will be linear and/or square root type. These are the major considerations for selecting a flow meter. In present days built in square root extractors are also available with DPTs.

6. **Power supply:** Power supply is essential for operation, remote transmissions, and/or remote displays. Similarly for pneumatic systems compressed air supply (1.4 bar) is essential. So, power supply type (bulk or single) and their locations are very important. With near obsolescence of pneumatic instrumentation, intrinsic safety circuits are used to cater to the requirements of power issues in hazardous atmosphere applications. In many applications, fiberoptics are also deployed. So, in the selection process due considerations should be given to these matters. For further details on these issues refer to Ref. [70]. For many remote applications solar-powered systems can also be used [69]. Similarly battery-operated meters are not uncommon, e.g., battery-operated electromagnetic flow meters from reputed manufacturers, e.g., ABB, for use in remote areas without power.
7. **Application limits:** Based on medium flow characteristics, and meter characteristics, meter selection can be narrowed down. However, this is not the end of the road. One also needs to check the application limits which come from different areas in the application proper, such as environmental condition, operating condition limits, pulsation vibration, etc. These are highlighted below to ensure that the selected meters also meet the application limits.
   - *Environmental issues:* When flow meters are selected their application and associated limitations must be taken into account. Site conditions are very important, because any meter has specific limit of use for environmental conditions such as temperature, relative humidity, salinity, etc. This is because the ambient conditions can only be adjusted to a limited degree to the requirements of the particular flow meter [1].
   - *Operating condition limits:* Apart from environmental issues, limitations also come from maximum operating pressure, temperature, and maximum line size. The thickness of the body is mainly responsible for the maximum pressure-withstand capability. Similarly, allowed thermal expansion, temperature limit from gasket type, lining material, and other material types decide maximum temperature-withstand capability. The manufacturer's manufacturing testing, etc. facilities often decide on minimum and maximum line size of the flow meter. For each type of meter the manufacturer's specification indicates the maximum operating pressure and temperature for which the flow meter can operate. Similarly there are lower and upper limits for pipe size for which a flow meter could be applied. Such a piping limit is more predominant for in-line instruments, like electromagnetic flow meters, vortex, swirl, etc. meters. Many instruments, including DPTs, are sensitive to mounting position, e.g., a variable area meter is only for vertical mounting and oval gear for horizontal mounting.
   - *Pulsation and vibration:* Pulsation in the system comes from the inertia of the

measuring system. When the measurement system does not show any lag in measurement then it is unaffected. This will affect the wear of the moving parts due to increase in wear. Vibration in the measurement system comes from vibration in the associated piping system. The measuring systems based on frequency measurements like some positive displacement meters will be affected. This will cause errors in measurement. Similarly some meters in generic terms do not show an effect related to pulsation and vibrations, e.g., electromagnetic flow meters/ultrasonic/mass flow meters do not show much effects to either pulsations or vibrations (in Coriolis mass flow meters vibration is decoupled) [1]. In contrast, positive displacement flow meters show a strong effect against pulsation as well as vibration (in terms of error and increased wear out).

- *Reverse flow:* In the case of a volumetric totalizing flow meter, the totalizing will be reversed. In contrast, electromagnetic flow meters and mass flow meters can measure bidirectional flow.

  In view of the above, manufacturers' specifications must be consulted properly prior to using the meter for the application, making sure the desired requirements for the application are met by the selected meter.

8. **Performance criteria:** Any flow-measuring system has some performance requirements. These include firstly the desired accuracy, repeatability, span of measurements, pressure drop, and long-term reliability. Accuracy, repeatability, and span have been discussed at length in Section 1.2.1 and hence are not repeated here. Here pressure drop indicates the permanent pressure drop which in turn is related to loss of energy. Naturally, meters that create less of a pressure drop are always preferred to minimize pumping losses. The relation between span and accuracy is an important issue. It may be seen that many instruments specify turndown (TD) 100:1 and accuracy of 0.075% of full-scale division (FSD). One must remember that both these *cannot* be true at the *same* time. This is one way of specifying instruments from a marketing strategy. In the majority of instruments the best accuracy of, e.g., 0.075% FSD is true really for TD of 6:1 to 10:1, beyond this TD, inaccuracy sets in. This will be clear from a thorough study of any reputed manufacturer's catalog. Therefore, it is important to compare all these parameters of flow meter types. For selected flow meters these important parameters have been enumerated in Table I/4.2.2.8-1. The values given in the table are average generalized values. For an accurate value one needs to go through a specific catalog from a reputed manufacturer of the particular device. Span (TD) values given in the table pertain to the specified accuracy and the instrument may have higher TD at the cost of accuracy (which is overall accuracy including repeatability).

   As indicated in Table I/4.2.2.8-1 for PD meters there are wide variations of TD. For oval gear it is 10:1 due to the fact that the same is a function of viscosity [1]. In defining the values of accuracy, linearity, repeatability, etc. same have to be taken into account. In this connection the VDI directive may be referenced. As indicated earlier, long-term reliability of the flow meter is an important issue. The mechanical wear primarily comes from abrasion of the metering elements due to flowing medium. This is also due to bearing friction of the moving parts. Naturally flow meters without moving parts such as electromagnetic/ultrasonic flow meters are better options.
9. **Meter installation and maintenance:** As stated earlier, the cost factor for flow meters is not only the initial cost but the lifecycle cost in which installation cost plays a major role. Apart from this there is the question of

TABLE I/4.2.2.8-1 Performance Parameters of Selected Flow Meter (Typical Only)

Meter Types	Span	Accuracy (%FSD)	Pressure Drop (Bar at Max. Flow)	Remarks
Head type meter	5:1/10:1	2*	Depends on DP and beta ratio	*Combined FE & DPT
Variable area	12:1	1.5*	Negligible	*Typical
Electromagnetic	50:1	0.1–0.2	Same as piping	As full bore
Ultrasonic	10:1	0.5%–1%	Same as piping	Generalized for both types
Coriolis	80–100:1	0.1	0.2–5*	*Meter style dependent
Thermal mass	40–150:1	0.5–1	Negligible	Type-dependent average values
Oval gear*	10:1	0.5	5	*Large variations in PD meters
Rotating vane*	300:1	2–3	<1	
Turbine	20:1	0.5	<1	Fluid dependent
Swirl/vortex	25:1	0.5–1	<1	
Impact	250:1	0.5–1	NA	*TD especially for weigh feeder is actually difficult, due to wide variations and requires detailed testing
Coriolis (solid)	200:1	0.5–1	NA	
Centripetal	10:1	0.5	NA	
Microwave	20:1	2%–5%	NA	
Weigh feeder	25:1*	0.2%	NA	

installation feasibility. This is more so in the case of a solid flow meter where there may be requirements for more space. When selecting a flow meter it is better if one plans the installations after preliminary selection of flow meter type, line size, pipe direction, material of construction, pressure rating, etc. In certain cases it is necessary to select appropriate connection type, tapping style e.g. flange type, and rating. In certain applications, the installation issue may arise on account of equipment accessibility, regulators, and available straight pipe run lengths etc. For a specific application, the designer needs to pay attention to all these as they may influence the flow meter selection process also. Almost all flow meters call for a run of straight pipe in upstream and downstream lines. Various types of disturbances, such as reducers, valves, etc. affect the velocity profile and these are different for different flow meter types. Flow meter centering and mounting of the flow meter are crucial for performance of the meter. Another issue is installation of meters in a pipeline to see that these are not subject to any stress. This is especially true when installing a meter in an existing pipeline. Many flow meters producing small signals are readily affected by external noise, therefore, suitable shielded cables with proper grounding are essential. The importance of grounding cannot be overestimated, especially for electromagnetic flow meters and flow meters with intrinsic safety circuits. Various requirements for grounding details of intrinsic safety circuits have been detailed in the author's book [24] and for intrinsic safe circuits [70]. Generally, flow meters with few or no moving parts require much less attention than complex instruments, because meters with moving parts can malfunction due to dirt, dust, and foreign matter. Meters with impulse lines may become plugged/blocked and are subject to wear. Almost all modern measuring devices are designed and developed in such a way that

maintenance personnel are able to monitor the proper functioning of the meter through simple tests and self-diagnostics. The majority of flow meters, including DPTs for head type measurements, are intelligent devices with the capabilities of self-monitoring and reporting errors.

4.3.0 Open System Flow Meter Selection

Free surface flows are mainly concerned with the flow of water or wastewater applications. Therefore, the discussions presented here are for liquid (water) with some solid and gas contents as is normally found in wastewater.

1. **Solid contamination:** In view of the low velocity of medium, carried settles in dammed area, solids ahead of a weir to cause measuring errors. Floating particles are liable to cause blockage of overflow areas. On account of acceleration in a flume in its constricted areas, solids do not settle and are driven out. The floating particles help built up of foam, which causes measurement errors.
2. **Entrained gas:** Entrained gas/air increases the measured volume flow and causes measurement error. For weirs, ventilation can reduce this measurement error.
3. **Flow regime effect:** The upper surface of the liquid causes measurement error on account of wave motion. This is more prominent in flumes than weirs.

4.4.0 Cost and Approval Considerations for Flow Meter Selection

Two other considerations, namely cost and approval, are very important. In this subsection these are dealt with.

1. **Cost considerations:** As indicated earlier, it should be the aim to look at the lifecycle cost, i.e., to take care of long-term ownership costs. It is interesting to note that a flow meter selected on the basis of the lowest price can often result in much higher costs for installation, testing, and maintenance. The supplier's backup support and expertise services are also for selection of an instrument on the basis of cost only (if suitable support is not available when needed the meter may have to be rejected). In the modern era, cost-effective installation would be one where the reputed supplier can offer good technical back-up, independently traceable test facilities, and IT compatibility through established sound research, and development facility of the manufacturer. Due consideration should also be given to cyber security [24] especially when the instrument is connected to a network through fieldbus system. It is a fact that usually meters for large systems will have higher cost than their counterparts in small systems. Obviously, for a specific design the cost may go high so, unless in an extreme case, it is better to stick to the standard design. Meters with additional data logging and/or telemetry facilities will incur additional cost, but keeping the cost within budget (such additional cost may have to be ignored) as it is system requirement. The product cost depends on total purchase price, along with installation and maintenance cost. This involves a thorough knowledge of the process and product. Overbuying is not uncommon. Basically, the selection of an appropriate flow meter is an aspect of the overall project design and costing.
2. **Approval requirements:** For meter selection another important issue is approval of the meter for various applications. Chemical firms need to comply with the requirements set by the US Environmental Protection Agency (EPA), North American Industry Classification System (NAICS), American Chemical Society (ACS), etc. to name but a few for North American industries. The situation is similar in other countries. Additionally, for hazardous applications the meter must comply with zone and/or class division classifications. For details of requirements on this, Ref. [70] may be referred to. This is mentioned here to indicate that while making the flow meter selection, due considerations must be given to this aspect also so that these can be used in specific applications.

4.5.0 Flow Meter Selection Matrix

From the above, it is clear that for meter selection a number of issues need to be thoroughly examined in selecting a meter for any specific application. The selection matrix presented below may be quite helpful in generic selection of a flow meter and/or to narrow down the selection process. With developments in digital electronics now it is quite possible that most of instruments support digital fieldbus communications. So, in cases where fieldbus is not mentioned (Table I/4.5.0-3), this does not mean it is not available. Only commonly available aspects have been mentioned, and it is quite possible that digital fieldbus communication is offered by some manufacturers. There are three tables presented here: Table I/4.5.0-1 for open-channel meters, Table I/4.5.0-2 for solid flow meters, and finally Table I/4.5.0-3 for closed-pipe fluid meters.

TABLE I/4.5.0-1 Open-Channel Flow Selection (Weir/Flume) [1]

Point of Comparison	Weir	Flume
Meter size	Unlimited	0.2–3.6 m
Maximum flow rate	Unlimited	~14,000
Turndown	100:1	20:1
Error % AR	3	6
Output/display	Local indication, remote transmission, analog/digital: HART, fieldbus	Local indication, remote transmission, Analog/digital: HART, fieldbus
Foreign matter	Solid: Deposit and floating particles error chances Entrained gas: With ventilation effect is less	Solid: Error chances due to floating particles in overflow Entrained gas: Degasser at upstream to reduce effect
Flow regime effect	Negligible	Has effect

Flume in generic way given above.

TABLE I/4.5.0-2 Flow Meter Selection Matrix for Solid Meters [43]

Point of Comparison	Impact Scale	Centripetal	Coriolis	Microwave	Weigh Feeder	Remarks
Accuracy % FSD	0.5–1	0.5	0.5–1	2–5	0.2*	*Prefeeder dependent
Flow range tons/h	Up to 900	40	Up to 600	20	800	
Turndown	250:1	10:1	200:1	20:1	25:1*	*Approximate, generic difficult to predict
Gravity feeding	Works well	Works nicely	Works well	Works moderately well	Works well	
Pneumatic feeding	Does not work well	Does not work well	Does not work well	Works moderately well	Does not work well	
Output/ indication	Remote transmission analog/digital fieldbus integration practically for all					

TABLE I/4.5.0-3 Flow Meter Selection Matrix for Closed Pipe Fluid Meters

Property	Electro Magnetic[b]	Coriolis Mass[c]	Thermal Mass[c]	Vortex/ Swirl	Head Type	PD Meter	Turbine	Rotameter	Ultrasonic[c]	Remarks
Overall accuracy	0.2%–1% AR	±0.15% –0.5% AR	±1.5% FS	±1% AR*	±0.5% –2% FS	±0.2% –0.5% AR	±0.1% –0.2% AR	±2% FS	±2% FS	*Re > 20000
Turndown	100:1	10–100:1	40–100:1	15–20:1	5:1	10–250:1	5–20:1	12:1	20:1	
Velocity (m/s)*	0.1	0.1	0.1–0.2	0.4 (L)	–	0.2	0.8	0.5	0.1	*Minimum
Velocity (m/s)*	12.5	10	10–12	9(L)/60(G)	8(L)/50(G)	5(L)/30(G)	9(L)/50(G)	8(L)/30(G)	10(L)/ 60(G)	*Maximum
Pressure loss	Negligible			2 times*	4–6 times*	2 times*	2 times*	1 times*	Negligible	*Vel. head
Diameter (mm)*	2–3000	3–200	3–200	15–300	25–2000	3–500	5–500	3–100	6–3000	*Typical
Calibration	Required			Not required		Required		Not. Reqd	Required	
Output[a]	A, H, FB, P	A, H, FB, P		A, H, FB, P	A, H, FB	A, H, P	A, H, P	A, local*	A,H, FB, P	*indication
Limit Temp. °C	–40:180	–200:240	<300	–200:400	–20:1000	10:300	–100:300	10:100	10:100	Min:max
Limit Pr. (bar)	40			64	600	100		200	100	
Viscosity (cst)	Below 10 to above 40 C/SC L*			>10 (USC)	>40 SC L*	>40 C (L)	>40 SC L	10-40 SC L	>40 C (L)	*MC–USC
Clean L	YES	YES	YES	YES	YES	YES	YES	YES	YES	
SC liquid	YES	YES	YES	YES (<10 cst)	YES	NO	YES	YES	USC*	*Doppler
MC/abrasive (L)	YES	USC	USC	USC	USC	NO	NO	NO	USC	
HC liquid	YES	NO	NO	NO	USC*	NO	NO	NO	NO	Lo viscosity

Continued

TABLE I/4.5.0-3 Flow Meter Selection Matrix for Closed Pipe Fluid Meters—cont'd

Property	Electro Magnetic[b]	Coriolis Mass[c]	Thermal Mass[c]	Vortex/ Swirl	Head Type	PD Meter	Turbine	Rotameter	Ultrasonic[c]	Remarks
Slurry	YES	YES	NO	YES	NO	NO	USC	NO	YES*	*Doppler
Clean gas (G)		YES			YES	YES	YES (>1 kg/m^3 USC)	YES	YES	
SC—gas (G)		YES			YES	No	YES (>1 kg/m^3 USC)	NO	YES	
MC—gas (G)		No			USC	No	No	NO	NO	
High humidity		YES -<1 kg/m^3 USC			USC	No	YES (<1 kg/m^3 USC)	NO	YES <1 kg/m^3 USC	
Density (kg/m^3) (Gas)		1 to >60 for <1 –USC			<1 to >60	<1 to >60	1 to >60 <1 –USC	<1 to >60	1 to >60 <1 –USC	

AR, actual reading; *C*, clean; *El. Magnetic*, electromagnetic; *FS*, full scale; *G*, gas (meaning compressible fluid including *steam*); *HC*, high contaminated; *L*, liquid; *MC*, medium contaminated; *No*, not possible/recommended; *PR.*, pressure; *Re*, Reynolds number; *SC*, slight contaminated; *Temp*, temperature in °C; *USC*, under special condition; *Vel. head*, velocity head; *Yes*, possible.
[a]*Output types;* A, *analog;* FB, *digital fieldbus communication;* H, *digital HART;* P, *pulse.*
[b]*Applicable for liquid > 5 μS/cm conductivity.*
[c]*In gas and steam application most optimistic values shown.*
This table is based on U. Endress, H. Hafelfinger, P. Hafner, A. Jaggi, G. Kempf, M. Lang, A. Schinke, K.H. Schulz, R. Silberman, K. Steiner, H. Thommen, P. Tschabold, P. Wetzer, E. Zeller, Flow Handbook, E+H Flotech A.G, 1989; F. Frenzel, H. Grothey, C. Habersetzer, M. Hiatt, W. Hogrefe, M. Kirchner, G. Lütkepohl, W. Marchewka, U. Mecke, M. Ohm, F. Otto, K.-H. Rackebrandt, D. Sievert, A. Thöne, H.-J. Wegener, F. Buhl, C. Koch, Deppe, E. Horlebein, A. Schüssler, U. Pohl, B. Jung, H. Lawrence, F. Lohrengel, G. Rasche, S. Pagano, A. Kaiser, T. Mutongo, Industrial Flow Measurement Basics and Practice, ABB Automation Products GmbH, http://nfogm.no/wp-content/uploads/2015/04/Industrial-Flow-Measurement_Basics-and-Practice.pdf; Flow Meter Selection Guide: Choosing the Correct Flow Meter, iCenta, UK, http://www.icenta.co.uk/knowledge-base/flow-selection-guide/.

5.0.0 DISCUSSIONS ON PERMANENT PRESSURE LOSS AND ALLIED ISSUES

Permanent pressure loss (PPL) in pipelines is concerned with fluid flow in a closed pipe. Currently there are several technologies available for the measurement of fluid flow in a closed pipe. The market share of most of them has been shown in Fig. I/5.0.0-1.

From the above it can be seen that, although head type measurement creates higher PPL, DP type (head type) meters occupy the major share. This means that PPL may not be the sole criterion for meter selection. However PPL has a great role to play in minimizing annual energy cost. Hence it is an important issue to discuss. Prior to starting the discussion it is important to go to the root of the issue and for this one needs to understand the fluid mechanics behind it.

1. **Brief fluid mechanics for PPL:** A pressure drop due to viscous effects represents an irreversible pressure loss, and is called pressure loss. So Eq. I/2.0.0-12; $P_1 + \frac{1}{2}\rho v_1^2 + Z_1\rho g = P_2 + \frac{1}{2}\rho v_2^2 + Z_2\rho g$ *is not true.* Rather, it is
$P_1 + \frac{1}{2}\rho v_1^2 + Z_1\rho g > P_2 + \frac{1}{2}\rho v_2^2 + Z_2\rho g$ so, by rearranging it can be written as

$$P_1/\rho g + v_1^2/2g + Z_1 = P_2/\rho g + v_2^2/2g + Z_2 + \Delta h_{ls} \qquad \text{(I/5.0.0-1)}$$

where, Δh_{ls} is called hydraulic loss (a scalar quantity). The hydraulic loss between two different cross-sections along the pipe is equal to the difference in total energy for this cross-section. This is given by $\Delta h_{ls} = H_1 - H_2$ and $H_1 > H_2$ for $Z_1 = Z_2$ and the diameter of pipe is constant $v_1 = v_2$ hydraulic loss is equal to the head of pressure drop or *head loss* $= \Delta h_l = (p_1 - p_2)/\rho g$. Head loss is expressed by the Darcy−Weisbach equation (for friction factor f, length L, and diameter D):

$$\Delta h_l = f \cdot (L/D) \cdot v^2/2g \qquad \text{(I/5.0.0-2)}$$

From this it is clear that there will be head losses in the pipe due to flow. This head loss is normally expressed in terms of equivalent length. Head loss for some common fittings has been enumerated in Table I/5.0.0.1-1.

All these have been stated here to indicate that pressure loss in the system due to flow is inevitable. Therefore, whenever any flow-measuring device is inserted in the pipe there will be pressure loss.

2. **PPL for flow meter:** Whenever a flow-measuring device is used in the line it creates some permanent (irrecoverable) pressure loss. One must not *confuse* pressure drop with pressure loss. Pressure drop occurs when a restriction is placed in a flow path. The pressure upstream of the restriction will be greater

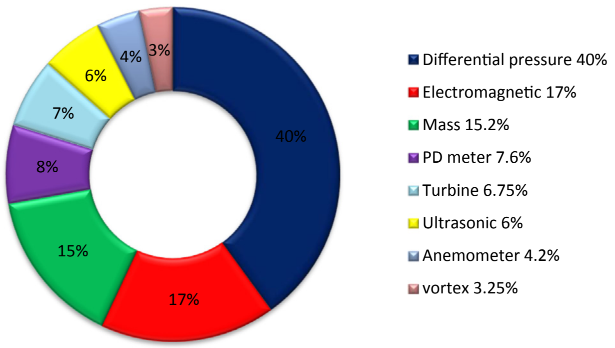


FIGURE I/5.0.0-1 Market share of selected fluid flow meters.

TABLE I/5.0.0.1-1 Head Loss Due to Some Selected Fittings

Fittings	L_e/D	Fittings	L_e/D
Gate valve, full open	8	90 degrees long radius bend	13
Ball valve, full bore	3	45 degrees long radius bend	10
Ball valve, reduced bore	25	Welded tee, thru' run	10
Globe valve, full open	320	Welded tee, thru' branch	60

than the pressure just downstream of the restriction. This is *pressure drop* and this happens due to change of pressure head into the velocity head. Further downstream from the restriction the pressure recovers to a new level that is lower than upstream pressure. The *difference* between the *upstream pressure* and the *recovered downstream pressure* equals the *permanent pressure loss (PPL).* As indicated above, this happens due to viscosity/friction loss. Several sources contribute to the pressure loss of a system, the most important being: pipe friction, valves, and measurement devices. With any new pipe section or equipment or instrument that is added in the flow line, there will be additional pressure loss. Fluid velocity and viscosity play an important role in pressure loss. This is valid for gases and steam as well as liquids in a closed pipe. So, the higher the fluid velocity, the greater will be the pressure loss. Permanent pressure loss is an important matter of which every engineer, designer, and technician should be aware [73]. From Bernoulli's equation we have seen that the amount of pressure lost in a flow meter depends on three factors: the fluid density, the square of the fluid velocity v^2, and viscosity along with other issues represented by meter factor K_{meter}. The degree of obstruction to fluid flow for a particular meter is represented by K_{meter}. Many flow meter technologies introduce pressure loss into a system. Some flow meters require upstream reducers and downstream expanders to operate properly. In the case of electromagnetic and ultrasonic flow meters, pressure loss is practically negligible. On the other hand, some flow meters have a more significant pressure loss due to their design. A Coriolis flow meter with curved tube or head type meters with their pipe restriction create pressure loss in the line. In terms of PPL, an orifice plate is less preferred to a Pitot tube. So, by replacing an orifice plate with a Pitot tube one can reduce the permanent pressure loss (energy requirement) by a factor of 20 [74].

3. **Importance of PPL:** Engineers and designers are keen to reduce PPL. Everybody likes to choose flow meters with permanent pressure loss as low as possible to reduce pumping energy and to increase steam boiler capacities. The aim of all these efforts is to trim the annual *energy spent* and thereby reduce the annual *cost* of energy. For new processes, engineers often consider PPL as a criterion for meter selection. This has also been indicated in the previous section. By minimizing pressure losses in a process, not only the cost of energy will be reduced but also the associated environmental impact will be reduced. By selecting flow meters with low pressure losses, engineers can:
   - reduce pumping/compressing costs [74];
   - increase capacity [74];
   - minimize compressor, pump, or boiler size [74];
   - minimize the associated environmental impact.
4. **Comparison of PPL for flow meters:** PPL in differential measurements is often done based on the beta ratio, i.e., the ratio of the diameter of the constriction to the diameter of the pipe. Because of construction, however in the case of V-cones calculation is slightly different, and is shown in Fig. I/3.1.1-9. For a beta ratio of 0.7, the area free will be 49%. Normally, in the case of a DP type flow meter it is stated as a % of DP value created (chosen). In such a case if 50% PPL is mentioned this means there will be 5 kPa PPL for a DP range chosen of 10 kPa. A curve based on beta has been presented in Fig. I/5.0.0.4-1.

   As per McCrometer's claim this is not a true comparison between the permanent pressure loss expected through the meters because the V-cone requires less differential pressure to remain accurate and repeatable [31]. Another way of establishing the PPL is based on the actual PPL. Such a PPL comparison has been presented in Fig. I/3.1.1-9. With little extension of the same, including a Pitot tube and V-cone, has been presented below in

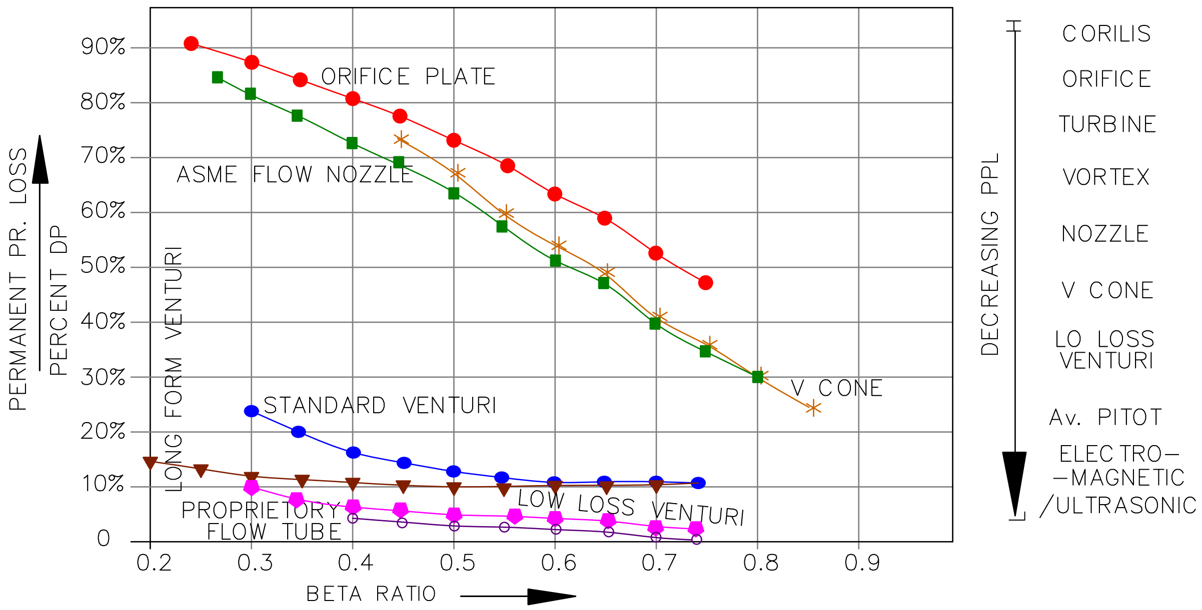


FIGURE I/5.0.0.4-1 PPL for FM. *Based on Permanent Pressure Loss Comparison Among Various Flow meter Technologies, McCrometer; White Paper; S. Basu, A.K. Debnath, Power Plant Instrumentation and Control Handbook, Elsevier, November 2014, http://store.elsevier.com/Power-Plant-Instrumentation-and-Control-Handbook/Swapan-Basu/isbn-9780128011737/. Courtesy: McCrometer.*

descending order of PPL, i.e., the bottom one is an ultrasonic/electromagnetic flow meter that will have negligible PPL and the Coriolis will have the largest PPL. This has been depicted in Fig. I/5.0.0.4-1 (right-hand side part).

From this we can gain a brief idea about PPL and how it varies with various flow meters. Similarly for installation testing calibration, etc. there are some good practices which are looked into in the Section 6.0.0.

6.0.0 PRINCIPLES AND GOOD PRACTICES OF INSTALLATION AND CALIBRATION

Preliminary issues concerning installation and calibration are discussed here.

6.1.0 Principles and Good Practices for Installations

Each type of meter has a unique issue concerning its installation and mounting. Detailed installation issues related to each type of instrument will be covered under the individual instrument category. The main emphasis here has been given to change of velocity profile and its effect on flow of fluid in a closed pipe. The most important issue that comes to mind is obstructions upstream and downstream of the flow meter, which are mainly responsible for velocity profile change. In order to combat these situations, there will be requirements for straight length of pipe; so that after mixing very near ideal velocity profile can be obtained. Therefore discussions on straight length requirement and if that is not possible how to manage the situation will be covered. The discussions presented here have been divided into two parts: background and the effect of the same on various types of instruments.

1. **Background:** From previous discussions in this chapter it has been shown that theoretically flowing fluid through a pipe assumes a uniform flow profile, with the greatest velocities near the center of the pipe. In reality engineers look out for a length of pipe, expressed in terms of a multiple of the pipe

internal diameter (ID) "D," which will allow the velocity profile, very close to an ideal one, to be developed. Fluid profile distortion may occur due an obstruction caused, e.g., by a partially open valve or a bend. When the flow faces a bend, it is forced against the pipe wall at the outside of the bend, then again rebounds towards the opposite side of the pipe, forming vortices as discussed earlier (Subsection 1.2.2.6). It is needless to say that these will result in measurement error. Two bends at different planes make the situation worse [75]. This will cause a single vortex or swirl formation, which may take hundreds of D to decay. So, it is noted that flow-profile distortion and swirl are two major disturbances encountered in flow metering. This might cause a partially blockage at a pipe by various fittings such as tee, elbow, valve, and even misaligned flange, as mentioned earlier. The result could be changing of the meter's flow coefficient. In order to circumvent these problems, piping configuration, i.e., straight lengths upstream/downstream, is very important. The less the straight run there is before and after the flow meter, the higher will be the error rate percentage (it may increase exponentially) [76]. Therefore, flow meter manufacturers and/or standards recommend various straight pipe lengths, both upstream and downstream, so as to get a fully developed desirable flow profile without disturbance. In many practical cases on account of space constraints it may not be possible to cater to these requirements. In such cases flow-straightening devices are prescribed to avoid long straight length requirements. Flow-straightening devices include tube bundles, perforated plates, and internal tabs [77]. Swirl, which occurs when the fluid moves through piping bends in different planes, is another and more difficult issue. Flow conditioners are used to reduce swirl.

2. **Installation issues for flow meters types:** From the above it has been made clear that distortion of flow profile and swirl affects the meter accuracy. Also, basic requirements to combat such effects have been addressed. However, profile distortion and swirl affect different flow meters differently. In Table I/6.1.0.2-1 such effects have been detailed. This mainly affects the fluid flow meters in a

TABLE I/6.1.0.2-1 Installation Effects of Fluid Flow Meters

Flow Meter	Distortion Effect	Swirl Effect	Others	Remarks
Head type measurement	Over reading except orifice. In orifice with lower beta, lower will be error	Higher and lower beta ratio will have over and under reading, respectively	Droplet, e.g., wet gas error in reading	Backward installation over reading
Coriolis meter	Not affected much		Incorrect alignment/ installation	Results in stress in meter
Thermal mass	Not affected much			
Electromagnetic	Not much effect by distortion and swirl. However for swirl bubbles/dirt present may affect vertical electrode. Better to use horizontal electrode			10D St. pipe upstream
Ultrasonic	Affects measurement depending on number of measurement paths			The higher the number of paths, the less will be the effect

Continued

TABLE I/6.1.0.2-1 Installation Effects of Fluid Flow Meters—cont'd

Flow Meter	Distortion Effect	Swirl Effect	Others	Remarks
PD meter	Not affected much		Variation of viscosity*	*Error in reading
Vortex	Affect reading by 3% [75] Up to 70D St. length upstream		Affected by pulsation/ vibration	
Turbine	Affected	Dependent on swirl direction for over and under reading*		Same and opposite direction cause over and under reading, respectively

closed pipe, therefore, major flow meters of this category have been included in the discussions.

3. **Straight pipe run (*thumb rule*):** From the above discussions it has been made clear that distortions and swirl cause measurement errors for which various standards and manufacturers recommends straight length requirements in terms of pipe ID "D." Such requirements not only depend on various types of obstruction in the pipeline but also on flow meter installations and orientation (e.g., vortex), sometimes it depends on the type of element and its beta ratio, e.g., orifice plate. In the case of a V-cone, on account of its self-flow conditioning, requirements of straight length are lower. Details of individual flow meter straight pipe run requirements are covered under the respective flow meter discussions. The thumb rule for straight length is in Table I/6.1.0.3-1 for quick reference. These data are only to get an idea and not to be used as data for design, for which the respective chapters may be consulted.

TABLE I/6.1.0.3-1 Thumb Rule for Straight Length Requirements

Flow Meter	Upstream (Times D)	Downstream (Times D)	Remarks
Head type	>10	5	Dependent on type of element and beta ratio
Mass flow	Not very specific (as very less affected)		
Electromagnetic	5	3	Minimum
Insertion type	20*/15 (25-ISO 7145)	10*/7.5	For meter size *<150 mm/>150 mm
Ultrasonic	5–6	2 (min)	
PD meters	Not very specific (as very less affected)		
Vortex	Wide 3–30*	>5	*Depending on obstruction
Turbine	10–15	5	

6.2.0 Principles and Good Practices for Calibrations

A short overview of the general principles of calibration for flow measurement will be given here. The discussions will be outline all the basic principles to be applied for calibrations. Calibration can be conceived of as a kind of comparison against a standard. The discussion starts with a fundamental question:

1. **Definition of calibration:** *What is calibration?*
   - *ISA definition:* As per "The Automation, Systems, and Instrumentation Dictionary" calibration is defined as "a test during which known values of measure are applied to the transducer and corresponding output readings are recorded under specified conditions."
   - *VIM definition: The International Vocabulary of General and Basic Terms in Metrology* (VIM)—an internationally accepted document. According to this, calibration is conceived of as an operation that, under specified conditions, establishes a relation between the quantity values (with measurement uncertainties) provided by measurement standards and corresponding indications (with associated measurement uncertainties) (VIM:2008).
   - *Other definitions of calibration and recalibration:* According to E. Loy Upp, author of *Fluid Flow Measurement* calibration of an instrument or meter is "The process or procedure of adjusting an instrument or a meter so that its indication or registration is in close agreement with a referenced standard." This concept is also well accepted. This involves the meter first being tested, then adjustments made for accurate reading. After the meter or measuring system is in service over a period of time then meter adjustments are also done to obtain the correct reading. This is referred to as *recalibration.*

   A proper understanding of the definition of calibration is very important as it does not represent "comparison." The "comparison" is applicable only for the conditions at the time of the calibration. Calibration is a confidence builder in accepting the measurement reading. In flow meters the mass/volume flow rate is established from the reading of the meter, when the density is known or measured. Flow in the process may be fast or slow as the case may be. Calibration of a flow meter should cover a significant flow-rate range for the flow meter so as to be able to establish a performance across that range. The choice of standard must also recognize the dynamic performance of the flow meter and the nature and resolution of the output [78]. Calibrating the process is required to provide cognizance of the resolution of the flow meter. Flow rate and meter performance (which indicates the expected performance of the meter to the measured performance) are the two major issues addressed during calibration. General calibration methods are discussed in Section 2.4.0 of Chapter II.
2. **Necessity for calibration:** From the above, it can be seen that calibration is performed by comparing or applying a known signal to the instrument under specified condition, to find the error. An error is the (algebraic) difference between the indication and the actual value. For a new instrument this is obvious, but the question may arise in somebody's mind: why is regular calibration essential as long as the device is working properly? The answer is very simple, in order to know that it is really functioning correctly calibration is needed. Apart from this, there are many factors which can cause a device to deviate from ideal position. These factors include but are not limited to the following (the last few factors are especially for mechanical parts).
   - Change of environment;
   - Drift;
   - Change in operating condition;

- Process change;
- Addition or deletion of component in the loop;
- Change of power supply;
- Corrosion;
- Erosion;
- Wear of moving parts;
- Aging.

  Error in the reading comes from a number of issues, for example, same measurement the response to a change by two instruments (even with same accuracy) may differ, because of sensitivity. Therefore, it is important to know the various related terms and their meanings.

3. **Commonly used terms:** A few commonly used terms have been defined below. It is found that people use these terms loosely and at times confusing one with the other. Another important issue here is that the definitions of many of these terms in VIM are from a calibration point of view and they may appear with a different approach when compared with generalized definitions given in Section 1.2.1 above.
   - *Accuracy:* As per ISA, accuracy is the ratio of the error to the full-scale output or the ratio of the error to the output, expressed in percent span or percent reading, respectively. In this connection Subsection 1.2.1.1 may be referenced. This is more related to the instrument proper. VIM:2008 conceive this as: Closeness of the agreement between the result of a measurement and a true value of the measure and recognized standard.
   - *Uncertainty (VIM:2008):* This represents a non-negative parameter characterizing the dispersion of the quantity values being attributed to a measure and based on the information used.
   - *Tolerance (ISA):* Permissible deviation from a specified value; may be expressed in measurement units, percent of span, or percent of reading.
   - *Repeatability (VIM:2008):* This stands for the measurement precision under a set of repeatability *conditions* of measurement (see Subsection 1.2.1.6).
   - *Reproducibility (VIM:2008):* This stands for measurement precision under reproducibility conditions of measurement.
   - *Resolution (VIM:2008):* The smallest change in a quantity being measured that causes a perceptible change in the corresponding indication (see Subsection 1.2.1.13).
   - *Traceability:* All calibrations that are performed should be traceable to a nationally or internationally recognized standard no matter how many levels exist between the calibration agency and nationally or internationally recognized standard. In case of the United States, it should be traceable to the National Institute of Standards and Technology (NIST). Traceability is accomplished by sending out the standard equipment (used for calibrating instruments) periodically to a standard laboratory with more accurate test equipment. The standard equipment from that standard laboratory is checked at a "higher level." Thus in this way traceability to a nationally or internationally recognized standard is established. This in a way conforms to VIM:2008 concept of traceability: "property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty."
4. **Calibration range and various errors in calibration:** In this part range for which an instrument is calibrated, zero, and span shall be discussed to see the effect of zero span error, linearity error, etc.

   The calibration range may be conceived of as the region between the limits within which an instrument has been calibrated for quantity measurement, receiving, and transmitting. This is expressed by stating the lower and upper range values consecutively. The limits

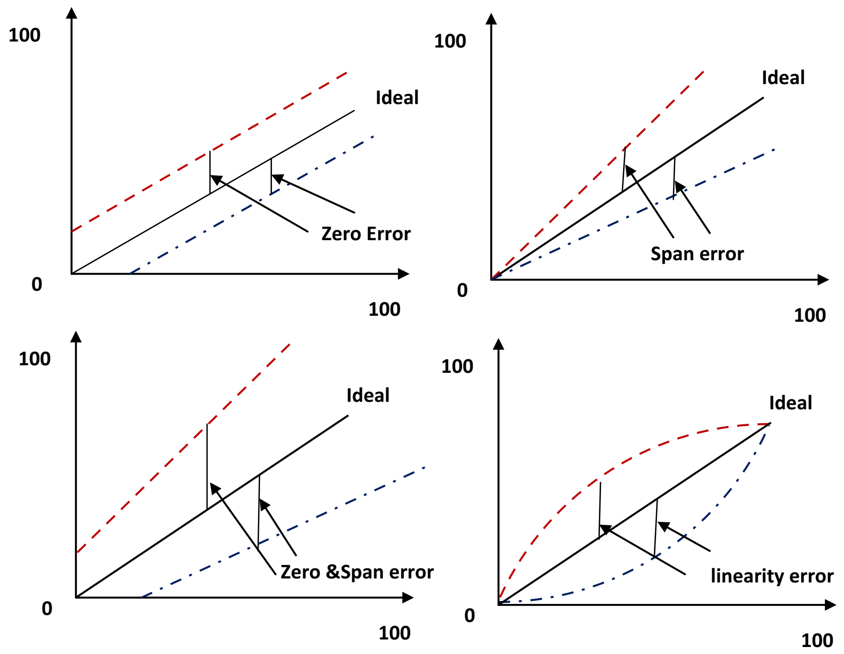


FIGURE I/6.2.0.4-1 Various errors in calibration.

are defined by the zero and span values. This definition is from ISA with slight modification to include the calibration term.

Zero: The lower end of the calibration range is zero.

Span: This is the algebraic difference between the upper and lower ranges. Any error can be corrected by calibration. Normally instruments have this adjustment facility.

Linearity: This is applicable only in cases where there is a linear relationship with output, e.g., magnetic flow meter. This is possible for those instruments which have linearity adjustment facilities. Otherwise if nonlinearity exceeds the tolerance limit, the instrument should be discarded and cannot be used.

Error: As already indicated in Subsection 6.2.0.2 there could be many reasons for errors occurring. In calibration zero error, span error, and a combination of zero and span error are important. Ideally the calibration curve should start from a lower range referred to as zero. An ideal curve is shown as a continuous line. In reality the zero value may be shifted to a new value causing an error, as shown in Fig. I/6.2.0.4-1.

It is to be noted that in the case of zero error the meter curve is parallel to the ideal curve with zero shifted. In contrast, in the case of span error the meter curve and ideal curve start from the same zero point but have different gradients. In the case of combined error of zero and span the meter curve is different from the ideal one. Most instruments have zero and span adjustment facilities for calibration. So, to know the condition of the instrument periodic calibration checks are essential. As stated earlier, the calibrating instruments must be checked in a standard laboratory periodically within its validity period and the calibrating instrument of the laboratory must have validity for calibration. In this way traceability is maintained.

6.2.1 FLOW METER CALIBRATION ISSUES

The discussions in the above sections are a little generalized in nature, but are more or less

applicable for process instruments. For flow measurement, process conditions and instrument types are also important considerations for calibration. A few such issues are discussed in this subsection.

1. **External influence:** Any flow measurement is a part of a process, so it changes with the dynamics of the process. Therefore, fluid flow measurements are affected in some way or another by the operating conditions of the process. This is dynamic and all measurement devices are affected in some way by the conditions of use. Also, each process is unique, therefore, flow instruments are subject to changes due to process conditions and their effects are also different. They are also affected by the external environment. For this reason it is impossible for any calibration system to mimic actual process conditions. In a calibration process a comparison is made between the output of the device under testing and that pertaining to the standard. This resultant relationship will be for the *specified conditions* [77] only. Also, the standard is influenced by various external issues and different types of instruments are affected by external issues differently. Selecting the standard is a compromise to best replicate the conditions of use while providing a suitable reference standard measurement [77]. Another important issue here is that the influencing factors affect the flow meter differently at different flow rates. It is therefore very important that the calibration is carried out for entire range to establish the relationship properly.
2. **Time of response:** Flow measurement is effected as rate quantity, so these are related through the time interval across which the quantity is measured. In flow meter calibration therefore the response time is critical. For a mechanical device, when the flow stops the register stops immediately. However, when a frequency counter is attached it will stop only after the measurement cycle is complete, which will have some delay. An electronic flow rate indicator will not show the correct instantaneous value. If however the mechanism in the meter has play or is loose, stopping the rotor may allow the output register to "run on" after the rotor stops, hence generating additional quantity or pulses [77]. Also, different types of measurement will have different responses. On account of inertia a turbine meter may take more time to slow down. In contrast, an electromagnetic flow meter takes some time to respond to the flow change due to voltage development time. For better performance in ultrasonic flow meters there are a number of measurements and the average of these is given as the output. Naturally, it will take some time to get the average value.
3. **Calibrating medium:** All flow meters always interact with the flow fluid. Such an interaction is dependent on the fluid property and velocity profile. Naturally, it is better always to choose the calibration fluid and condition as close to those in the real world. This is not possible in most of cases. Normally water/air are used as flow media in calibrations. The best economic compromise must be established in choosing the calibration. This will be based on the final duty of the meter, the required uncertainty, and knowledge of the meter performance [77]. Head type meters are highly dependent on Reynolds number so it could be done in different (than operating) fluids, maintaining Reynolds number variations. Turbine flow meters are very sensitive to viscosity. A turbine meter should be calibrated at the same kinematic viscosity at which it will be operated in service. For this reason, for oil applications dedicated meter provers are used. Also, as per NIST, meter provers are recommended for turbine meters (*e.g., turbine meters are calibrated using NIST's volumetric based, 20-L piston prover with a 1.2 Centistoke (20°C)* PG + W mixture). However, use of a master meter for this purpose is not

uncommon. For gas flow meters air is normally used as the medium. In gas flow measurement in turbine and ultrasonic meters, the Reynolds number could establish a good relationship. Gas pressure is the most important issue in gas meter calibration as it influences density and meter functioning. For variable areas, rotameter density correction is important.

4. **Velocity profile:** From the discussions on installation good practices in Subsection 6.1.0.1 it is clear that for better performance straight length of pipe is essential. Similarly, for calibration, set ups should have adequate straight pipe lengths and the use of flow straighteners and conditioners to establish predictable and reproducible flow profile as close as possible to an ideal profile. It is important to ensure pipes upstream of the meter have the same internal diameter as the meter inlet and step changes or misalignment of joints and gaskets do not introduce irregular profiles [77].
5. **Correction and K factor:** Normally in connection with flow meters there are two factors commonly used. These are the meter factor and K factor or pulse factor.
   - *Meter factor:* As per VIM this is the correction factor. The correction factor is a dimensionless constant numerical factor, by which the uncorrected result of a measurement is multiplied to compensate for (systematic) error (VIM). It is calculated as the ratio of the meter output to the value determined by the standard. This can be applied for quantity measurement or rate measurement. So, $F = V_s/V_i$ or $F = Q_s/Q_i$ where i is the meter reading and s is the standard. Q and V have the usual meanings.
   - *K factor:* When measurements are done as a pulse count, then the K factor present is the number of pulses per unit quantity. It is different for different meters.
6. **Five major steps for flow meter calibration:** From the above discussions one can summarize the following five major steps:
   - *Standard used:* The standard used for calibration must be highly accurate. Empirically it should have at least four times higher accuracy than that for unit under test (UUT) [79].
   - *Traceable:* The standard used for calibration must be traceable to any recognized national/international standard.
   - *Steady flow:* The flow between the standard and UUT must be in steady state otherwise there may be inaccuracy [79].
   - *Same medium:* The medium flowing between the standard and UUT must be identical, i.e., no leak, etc.
   - *Calibration condition:* The flow calibration should be carried out in conditions as close as possible to the actual application (especially for certain types of meters).

   With this the discussions on good practices for installation and calibration come to an end and we now discuss another most interesting flow-measuring device, the sonic nozzle, which because of its construction does not depend on differential pressure.

7.0.0 CRITICAL OR SONIC NOZZLE

The sonic nozzle, often referred to as a "critical flow nozzle/Venturi," is used for gas flow measurement, mass flow measurement, and on account of its accuracy it is also used as a calibrating standard for other instruments. *What is a sonic nozzle?* A "sonic nozzle" is also known as a "critical flow nozzle/Venturi." This is a high-accuracy flow meter which can be used as a calibration standard for gas flow meters or other flow measurement devices. With the use of regulated pressure the sonic nozzle can be used as a very precise mass flow meter.

7.1.0 Features and Advantages of Sonic Flow Nozzles

There are a few basic features and advantages that make this flow-measuring device unique. Some of these features and advantages are elaborated on below.

1. Internationally recognized flow meters [80];
2. No moving parts;
3. Measurement is not dependent on DP across it;
4. Single-pressure measurement and DP measurement are not required;
5. Flow varies with inlet pressure (outlet vacuum) [81];
6. Mass flow varies linearly with inlet pressure;
7. Upstream straight length requirement is minimum;
8. Flow measurement unaffected by downstream disturbance;
9. Excellent long-term accuracy and repeatability.

7.2.0 Applications of Sonic Flow Nozzles

Sonic flow nozzles have application areas in flow measurement and control, especially in automotives. Application areas of sonic flow nozzles include but are not limited to the following.

1. Precision gas flow measurement;
2. Calibration of gas flow metering system;
3. Calibration of turbo engine and automotive components;
4. Automotive emission tests;
5. Control valve (CV) checks;
6. Controlled flow and flow limiting.

7.3.0 Functional Details of Sonic Flow Nozzles

The discussion on sonic/critical flow nozzles/Venturi starts with Fig. I/7.3.0-1.

As can be seen in Fig. I/7.3.0-1A there are three distinct sections to a sonic flow nozzle.

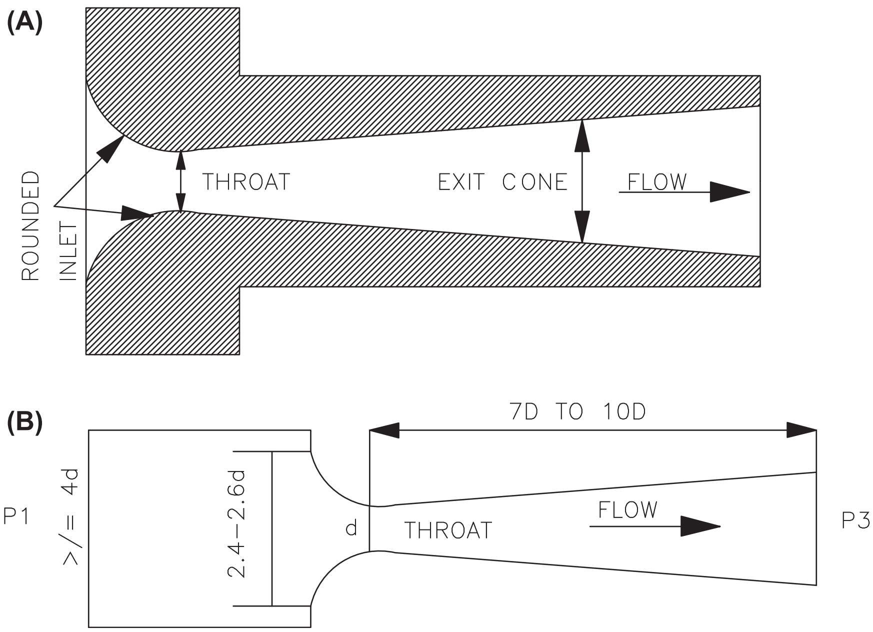


FIGURE I/7.3.0-1 Sonic flow nozzle. (A) Sonic flow nozzle sections. (B) ISO Torodial throat critical nozzle.

(1) Smooth rounded inlet section, followed by (2) minimum area throat, and finally (3) diverging section for pressure recovery, i.e., exit cone. In this connection, Fig. II/3.6.0-1 may be referenced also. When gas with pressure P_1 enters it accelerates, meaning velocity increases but density decreases. It reaches maximum velocity at a minimum area at the throat. At this point it reaches the speed of sound (Mach 1). The sonic flow nozzle is usually operated by inlet pressure P_1 with pressure outside the sonic flow nozzle being P_3. However, it is also possible to operate by evacuating outside P_3 to obtain sonic nozzle operation. The major criterion is that P_1/P_3 should be $>1-1.4$. This ratio maintains the choked condition at the throat. Thus at this point only the inlet pressure and temperature can regulate the flow. In this situation the flow rate is almost linear with inlet pressure P_1. In its simplest form, by using the inlet pressure regulator, flow can be varied [81]. Downstream disturbance does not affect the flow because it cannot reach the throat, where the velocity is higher in the opposite direction, and hence velocity and density remain unaffected. For this reason it finds a number of applications for steady flow with downstream fluctuations. Also, unlike subsonic flow nozzles, DP is not measured and in subsonic flow nozzles the downstream disturbance affects DP and hence flow. This does not apply here. It can offer long-term accuracy of 0.25% AR. An ISO Torodial critical flow nozzle/Venturi, shown in Fig. I/7.3.0-1B, has various dimensions as specified.

In a sonic flow nozzle the mass flow rate q_m is proportional to the inlet pressure P, and is also related to temperature T by the following equation.

$$q_m \alpha P / \sqrt{T} \qquad \text{(I/7.3.0-1)}$$

The sonic nozzle is discussed further in Section 3.6.0 in Chapter II. With this discussion on the sonic flow nozzle concluded, we concentrate on some other types of flow-measuring techniques.

8.0.0 MISCELLANEOUS FLOW MEASUREMENT SYSTEMS

In this section about miscellaneous instruments, a few instruments will be discussed that are popular in industries but are mainly deployed for some specific applications, except cross-correlation meters, e.g., aerofoil is mainly deployed for air flow measurement in large duct, British thermal unit (BTU) meters which find their major applications in HVAC.

8.1.0 Aerofoil in Air/Gas Flow Measurement

Aerofoil is a differential producer used to measure air/gas flow in large ducts. Boiler air flow measurement with aerofoil is quite common.

8.1.1 AEROFOIL WORKING PRINCIPLES

Aerofoil is a differential pressure producer used to measure air/gas flow in ducts of various sizes and shapes (square and rectangular). It is used in those places where it is difficult and costly to put other DP producing elements. It requires much less straight length. An aerofoil has the shape of an aircraft wing cross-section. This produces a controllable net aerodynamic force. Aerofoil works on the principle of the relationship between flow velocity and the pressure fields in frictionless flow. As the air/gas particles follow the curved streamlines above the upper surface, there will be a centripetal force across the streamlines which accelerates the flow towards the center of curvature. That force is associated with a pressure gradient across the streamlines, i.e., ambient atmospheric pressure at some distance from the surface grading to a lower pressure on the upper wing surface. A typical aerofoil assembly with cross-sectional details and tapping points has been depicted in Fig. I/8.1.1-1. Usually two aerofoils are used for measurement, however more may be used. Fluid passes between foils to

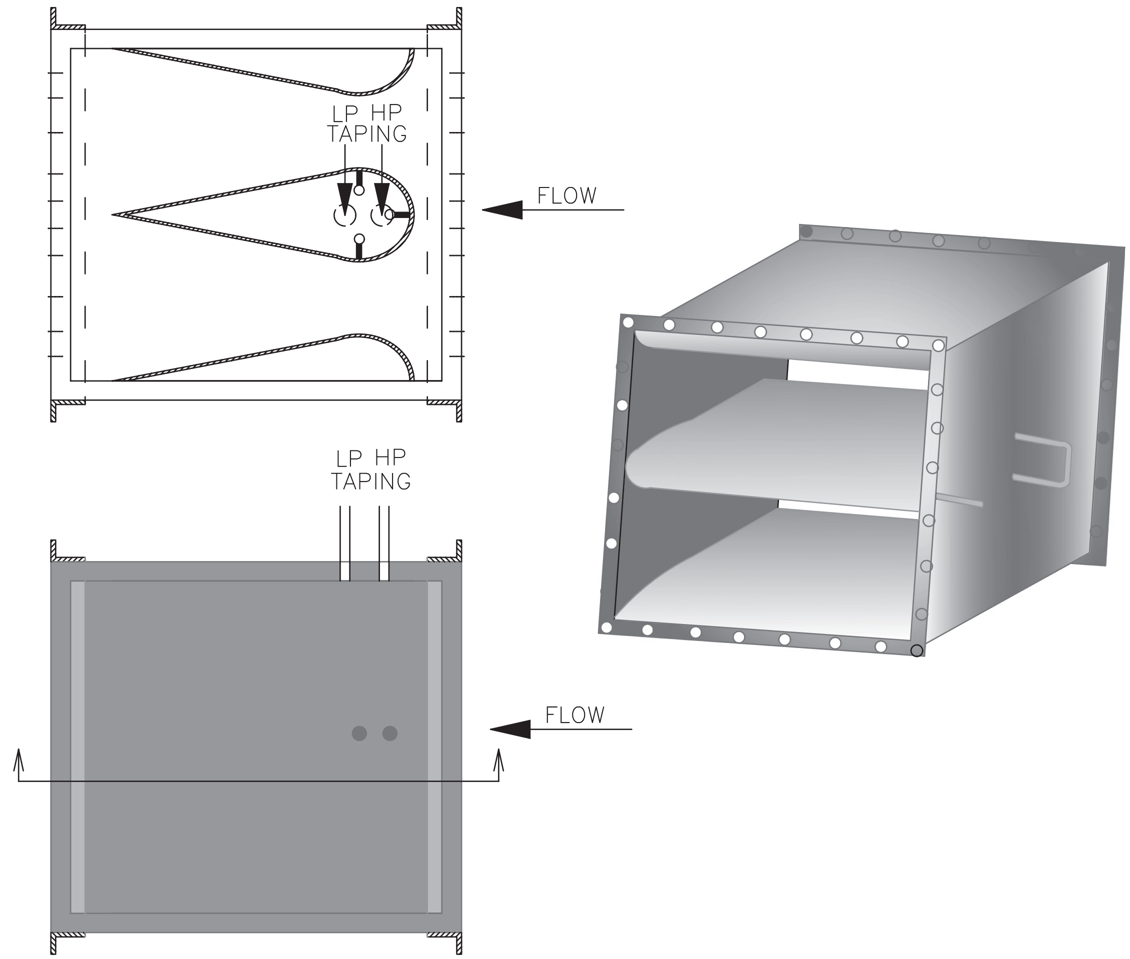


FIGURE I/8.1.1-1 Aerofoil.

create pressure drop. Pressure sensing is carried out at the face and back side for measurement of DP (upstream and downstream respectively).

8.1.2 AEROFOIL FEATURES

Aerofoil flow measurements do not have moving parts and are almost maintenance-free;
Less requirements for straight length;
These are applied in low-pressure applications;
Not suitable for higher viscosity;
Throat tappings are used;
Available in various size from 500 to >3000.

8.2.0 British Thermal Unit Measurement

In this era of scarcity of energy, an energy-efficient plant design is an important criterion. The importance of reliable energy audit towards this cannot be overestimated. In this area of application, a BTU meter plays a great role in checking and judging the coefficient of the performance or the efficiency of the individual heat exchanger. After energy audit and implementation of energy optimization steps, BTU measurements are normally carried out to note the good effects of optimization.

1. **BTU meter concept:** *What is a BTU meter?* As the name implies it measures the energy flow. BTU meters measure the energy content of fluid flow in British thermal units (BTU). It is a basic measure of thermal energy.
2. **Development:** Initially BTU measurements were carried out by mechanical means, but these were replaced by electronic versions. At present, with the advancement of signal processing there are compact BTU meters.

8.2.1 BRITISH THERMAL UNIT METER WORKING METHODS

As stated above in BTU measurement the energy content of fluid flow is measured. Naturally, the role of the fluid flow meter is very important.

1. **Mechanical BTU measurement:** In mechanical BTU meters, fluid flow is measured volumetrically by a positive displacement flow meter and mechanical movement is transmitted through gear trains. The temperature rather than the temperature difference between the cold and hot sides of the heat exchanger is sensed by a filled thermal bulbs system (for details refer to any standard book on process instrumentation). Dual CAM systems are used to utilize the aforesaid movement in computing BTU. These systems are rarely used nowadays.
2. **Electronic BTU measurement:** Electronic BTU measurement systems are shown in Fig. I/8.2.1.2-1. In electronic BTU measurement, flow and temperature upstream and downstream of heat exchangers are measured separately by flow meters and temperature elements and transmitters, respectively.

All these signals are sent to the BTU computing unit as shown in Fig. I/8.2.1.2-1A. Basically at this unit all signal processing and computations are done. Usually these BTU computing units are standalone systems where all parameter values can be displayed along with cumulative flow and BTU. They can also display total BTU/hour. There are provisions for all signal retransmissions and/or for digital communication by fieldbus.

These instruments can offer much better performance and facilities than their mechanical counterparts. However, electronic systems are costlier than the mechanical type. The electronics system described is the traditional type where the heart is the computation unit and instrumentation may be from different sources. In this kind of arrangement total energy error could be as high as 5%−10% of the reading [82]. With the development of embedded microcontrollers and field programmable gate array (FPGA) (for microcontroller and FPGA details refer to Ref. [70]), compact programmable BTU meters with sensors are available as shown in Fig. I/8.2.1.2-1B. These modern meters are available with factory calibration and are traceable. These units offer an accuracy of 1.5%−1.8% AR [82]. In this connection Section 4.0.0 of Chapter XI may be referenced.

8.2.2 SENSORS USED IN BRITISH THERMAL UNIT MEASUREMENT SYSTEMS

In BTU measuring systems there have been a number of flow meters used, as described below.

1. **Mechanical system:** In mechanical systems, as stated earlier, flow meters are of the positive displacement type to take the advantage of their movement. Similarly fluid-filled thermal systems are used to get the mechanical movement of a Bourdon spring.
2. **Traditional electronic system:** Flow measurements are usually by turbine meter and temperature sensing by resistance temperature detectors (RTDs).
3. **Modern electronic system:** Temperature is measured by RTDs. The flow can be sense by:
   - orifice plate;
   - turbine meter;
   - insertion type magnetic flow meter;
   - insertion type turbine flow meter;
   - insertion DP (Annubar);
   - clam on ultrasonic;
   - insertion vortex.

   The in-line version of the above meters can also be used. In-line direct BTU meters are also available for smaller system applications. For wide area BTU monitoring telemetry can be deployed. Detailed discussions of BTU meters have been presented in Section 4.0.0 of Chapter XI with more details.

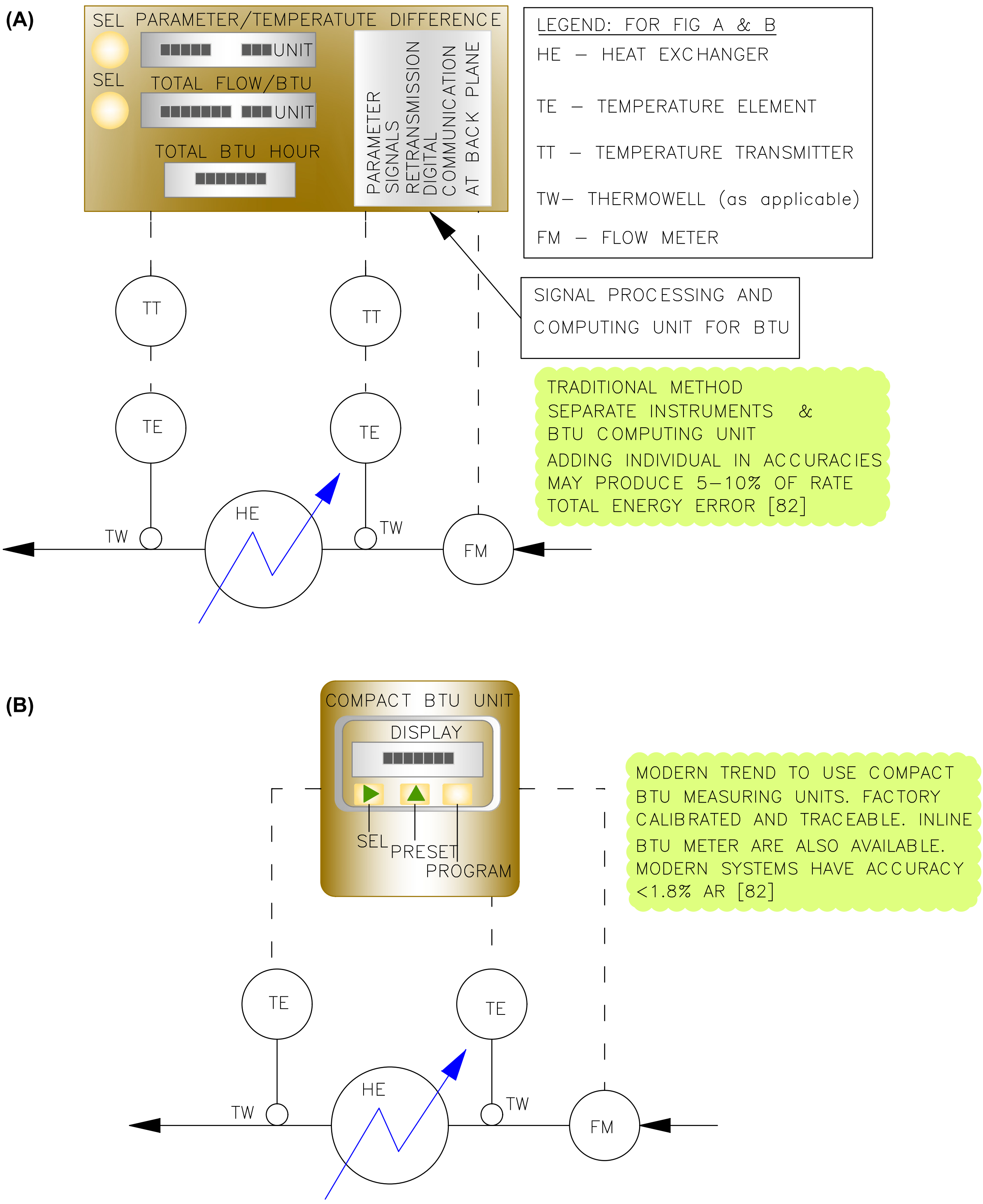


FIGURE I/8.2.1.2-1 Electronic BTU metering. (A) Traditional electronic BTU measurement. (B) Modern electronic BTU measurement.

8.3.0 Cross-Correlation Flow Measurement

The basic principle of cross-correlation has a close resemblance to the tracer technique mentioned earlier, for measuring flow velocity. Here the main difference is that instead of injecting a foreign substance into the fluid, the tracer is provided by some detectable random variable existing naturally in the flow [83]. In the cross-correlation technique there will be two sets of normally the same type of sensors along the flow path in the pipe. By cross-correlation technique, measurable process variables in a noisy environment can be used to build a correlation flow meter, provided the noise pattern persists long enough to be seen by both detectors [12] which are located along a flowing stream. In most the measurement's average velocity is the basis for flow computation. As stated earlier, flow profiles are distributed about the pipe cross-section. Also there are velocity fluctuations of the main flow or there will be different regions of turbulence intensities, especially due to piping configurations. Therefore average velocity measurement is not easy. In contrast, in the case of the correlation principle, there will be one key parameter, the distance "l" between the sensors, that is required. As shown in Fig. I/8.3.0-1 two sensors, A and B, are "l" distance apart and they produce two curves x(t) and y(t), respectively. The peaks of the two signals are transit time τ apart and this is computed by cross-correlation to find the velocity by dividing distance "l" by transit time τ.

8.3.1 THEORY OF OPERATION

1. **Cross-correlation method:** As shown in Fig. I/8.3.0-1 two sensors are placed a known distance "l" apart along the flow pipe. The continuous signals from each of them, i.e., x(t) and y(t), are compared, to find the delay time interval τ at which both signals have the maximum *similarity*. This is shown by two curves in the middle. Delay time τ and known distance "l" are used to calculate the velocity:

$$v = l/\tau \qquad \text{(I/8.3.1-1)}$$

Now the task is to find the delay by establishing the correlation. The delay time is obtained by convoluting (for details refer to any standard book of mathematics/statistics) continuous randomly varying input signal x(t) is with y(t), i.e., multiplied and integrated with suitable time displacement. Let the correlation function be $Rxy(\tau)$, then it is given by

$$Rxy(\tau) = \lim_{\tau \to \alpha} \frac{1}{\tau} \cdot \int_0^T x(t) \cdot y(t+\tau) dt \qquad \text{(I/8.3.1-2)}$$

Actually, by definition minus to plus infinity is the limit of integration. In the measurement, as the time domain starts from 0, the integration limit is set from 0 to infinity. From Fig. I/8.3.0-1 it is clear that x(t) is the signal of the upstream sensor (A) at time t, so downstream sensor (B) signal will be $y(t+\tau)$ delayed by a time τ. T is the integration time. Now function can be plotted against the time axis. The maximum of the functional plot is at τ_m, which represents the mean transit time of travel of fluid from the upstream sensor (A) to the downstream sensor (B). To summarize, from sensors signal curves are generated, and from the curves, the transit time is calculated as detailed in Fig. I/8.3.0-1. Thus for nonzero mean $\bar{x}$ and $\bar{y}$ for signal functions x(t) and y(t), respectively, *normalized* cross-correlation function $\rho_{xy}(\tau)$ can be obtained from covariance of $C_x(\tau)$, $C_y(\tau)$, and $C_{xy}(\tau)$. This is given by

$$\rho_{xy}(\tau) = \frac{Cxy(\tau)}{\sqrt{Cx(0) \cdot Cy(0)}} \qquad \text{(I/8.3.1-3)}$$

The cross-correlation function always lies between (−)1 and (+)1. The significance of

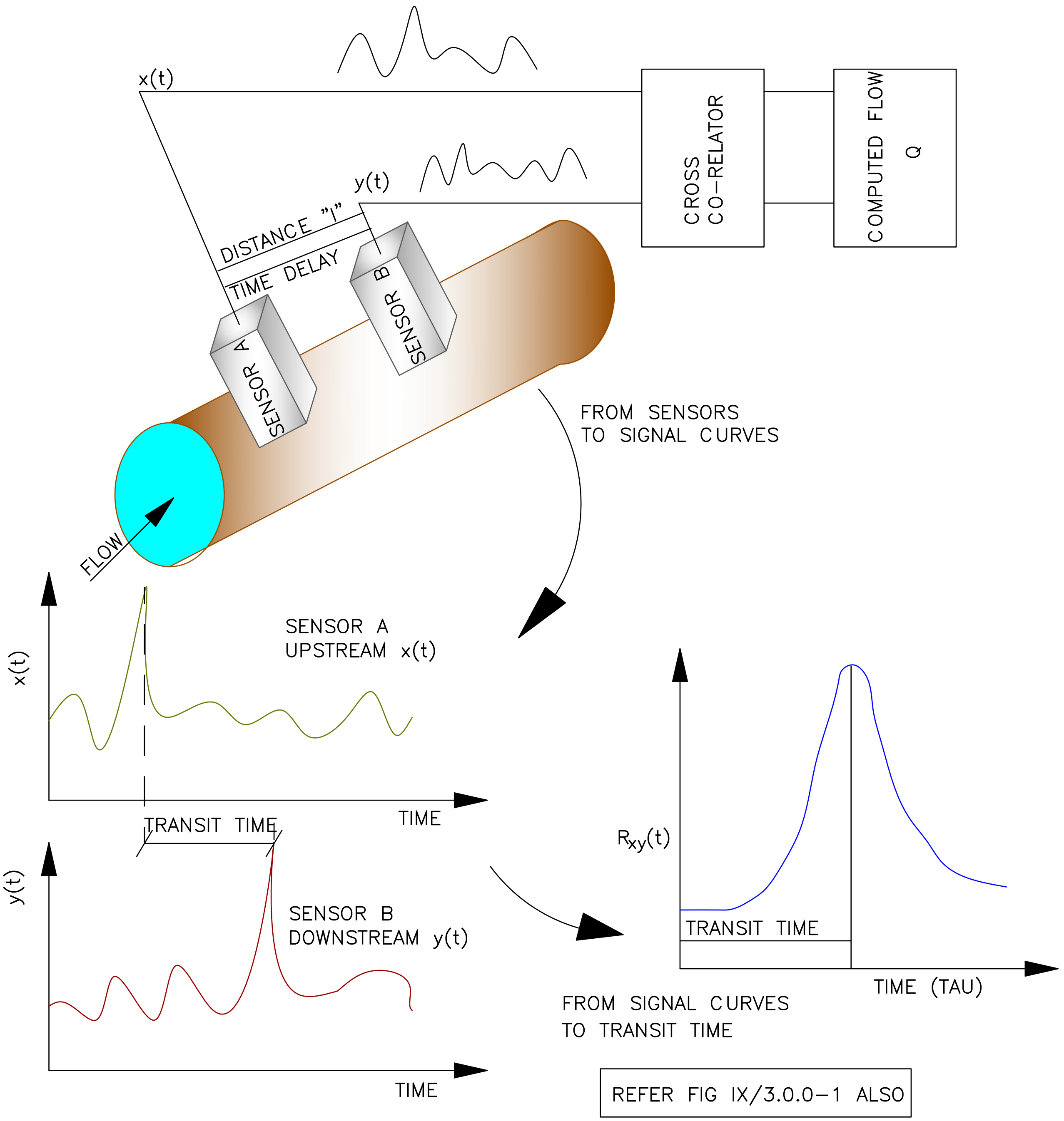


FIGURE I/8.3.0-1 Cross-correlation flow measurement.

this is that when cross-correlation is close to (+)1 there is a good direct correlation while close to (−)1 there is a good inverse correlation, and zero means no correlation between the variables. There is one distinct advantage in cross-correlation, that spurious signals in y(t) will automatically be rejected as they do not have any correlation with x(t).

2. **Point by point method calculation:** In digital systems which actually use a correlator, the integration in $R_{xy}(\tau)$ is used as a large sum as shown in Eq. (I/8.3.1.2-1) below.

So, Eq. (I/8.3.1-2) can be rewritten as

$$R_{xy}(J\cdot\Delta t) = \frac{1}{n}\sum_{i=1}^{n} xi\cdot y(i+j) \quad \text{where } j = 1,2\ldots J \tag{I/8.3.1.2-1}$$

(in Eq. (I/8.3.1.2-1), i and i + j are suffixes of x & y, respectively).

In this method, as the name suggests, the large sum is expanded in small intervals Δt and these are summed up in Eq. (I/8.3.1.2-1). Thus

$$R_{xy}(0) = x_1y_1 + x_2y_2 + \ldots x_ny_n$$

$$R_{xy}(1\cdot\Delta t) = x_1y_2 + x_2y_3 + \ldots x_ny_{n+1} \quad \text{in this way} \tag{I/8.3.1.2-2}$$

$$R_{xy}(J\cdot\Delta t) = x_1y_J + x_2y_{J+1} + \ldots x_ny_{n+J}$$

Eq. (I/8.3.1.2-1) shows the entire series sum. When for each Δt, R_{xy} is calculated and plotted against each Δt, a curve like that shown with various implementation methods in Fig. I/8.3.1.2-1A will be available. This curve may be compared with the same shown in Fig. I/8.3.0-1.

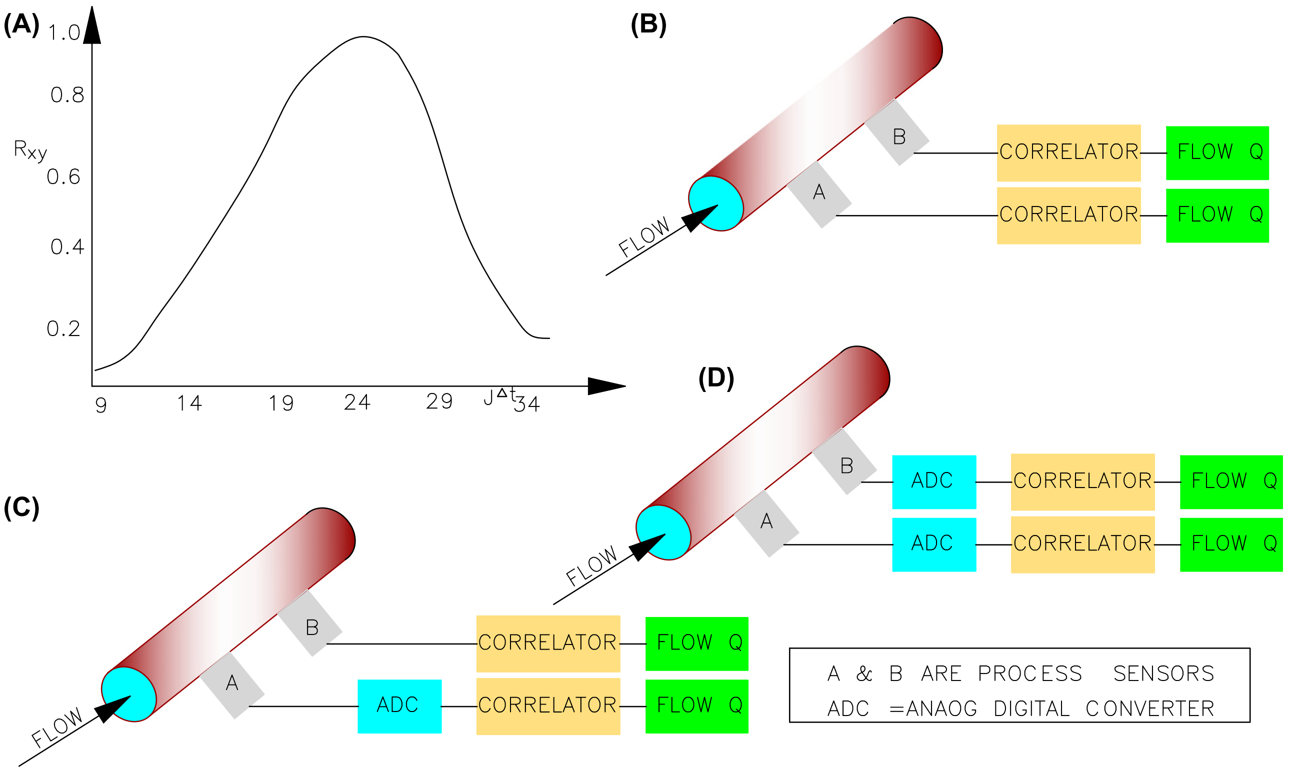


FIGURE I/8.3.1.2-1 Cross-correlation implementation. (A) Point by point correlation curve. (B) Direct analog signal implementation. (C) Mixed analog digital implementation. (D) Digital signal implementation. *This figure is based on an idea from E.J. Avilán, V. Reis, L.E. Barreira, C.M. Salgado, Evaluation of cross correlation techniques to measure flow in pipe of the oil industry, 2013 International Nuclear Atlantic Conference – INAC 2013, Associação Brasileira de Energia Nuclear – ABEN, November 2013, ISBN: 978-85-99141-05-2, http://carpedien.ien.gov.br/bitstream/ien/1788/1/EVALUATION%20OF%20CROSS%20CORRELATION%20TECHNIQUE%20TO%20MEASURE%20FLOW%20IN%20PIPES%20OF%20THE%20OIL%20INDUSTRY.pdf.*

3. **Implementation of correlation:** When for each Δt, R_{xy} is calculated and plotted against each Δt, a curve as shown in Fig. I/8.3.1.2-1A will be available.

   This curve may be compared with the same shown in Fig. I/8.3.0-1. The correlation given in series sum Eq. (I/8.3.1-1) can be implemented in one of the three methods discussed below [83].

   - *Direct method:* Both analog signals are sent to the computation unit for correlation as shown in Fig. I/8.3.1.2-1B.
   - *Relay method:* In this method one signal is digitized and sent to the correlator as shown in Fig. I/8.3.1.2-1C.
   - *Polarity method:* As shown in Fig. I/8.3.1.2-1D, here both signals are digitized before sending to the correlator.

4. **Alternative transit time determination:** Transit time may be determined from the standard phase frequency relation. If F is frequency and ϕ represents the phase then

$$2\pi\Delta F \cdot T = \Delta\phi;$$

and

$$2\pi\Delta F \cdot \tau = \Delta\phi;$$

where ΔF stands for the frequency band of highest coherence.

Thus we get

$$\tau = \Delta\phi / 2\pi\Delta F \qquad \text{(I/8.3.1.4-1)}$$

8.3.2 ACCURACY CONSIDERATIONS AND APPLICATIONS

From the discussions in Section 8.3.1 it is very clear that the time delay of the two signals is the key factor. Naturally the accuracy of measurement is highly dependent on τ. Also, as this method is based on statistical operations and relations, it is needless to mention the importance of statistical error. As in any statistical process, when the number of data points decreases statistical error increases. Flow measurement accuracy depends on *delay time* of peak value *not* on the *magnitude* of the same. For improved cross-correlation systems the following may be looked into.

The response of two sensors should be similar and should be faster than the process changes expected.

The correlation between the data does not occur at or after the break frequency of the sensor and/or the data acquisition system [12].

Generally two of the same type of sensor are used, but two different sensors could be used. Ultrasonic instruments are quite often used. For multiphase flow measurement cross-correlation flow meters are quite often used.

8.3.3 DISCUSSIONS ON CROSS-CORRELATION MEASUREMENT

Cross-correlation is very useful tool or system for analyzing time-invariant systems and system identification dynamics. The establishment of a close mathematical relationship makes it easier, as already discussed above. A major application area of cross-correlation is flow measurements in multiphase flow measurement and difficult fluids such as; pneumatically conveyed solid materials, slurries, and sewage to name some good examples of cross-correlation types of measurement. "… Non-contact and very robust cross correlation measurement techniques has a very far along measurement echelon in ideal conditions and are becoming widely used …" [84]. As mentioned above, basically the principle of this method is simply to measure the time taken by a disturbance to pass between two points spaced along the direction of the flow. US and electrostatic techniques are frequently used, such as pulverized fuel velocity in coal-fired power stations, utilizing a dynamic electrostatic technique (ABB).

With this, flow metering general discussions come to an end and next we go into more details on various types of flow meters starting with head type measurement.

LIST OF ABBREVIATIONS

BFP Boiler feed pump
CCW Counterclockwise
CE Coanda effect
CEMA Conveyor Equipment Manufacturer Association
CT Computerized/computed tomography
CW Clockwise
DP Differential pressure
DPT Differential pressure transmitter
ECT Electrical capacitance tomography
EIT Electrical impedance tomography
emf Electromotive force
EMT Electromagnetic tomography
EPA Environmental Protection Agency
ERT Electrical resistance tomography
FE Flow element
FM Flow meter
FPGA Field programmable gate array
FSD Full-scale division
GLR Gas liquid ratio
GOR Gas oil ratio
GVF Gas volume fraction
HART Highway addressable remote transducer
HVAC Heating ventilation and air conditioning
IPT Industrial process tomography
IT Information technology
IUPAC International Union of Pure and Applied Chemistry
KE Kinetic energy
LHS Left-hand side
LIW Loss in weight
LVDT Linear variable differential transformer
ME Momentum exchange
MFM Multiphase flow metering/measurement
MVT Multivariable transmitter
NMR Neuron/nuclear magnetic resonance
NTP Normal temperature pressure
O&M Operation and Maintenance
PD Positive displacement
PE Potential energy
PID Proportional, integral differential
PPL Permanent pressure loss
PT Pressure transmitter
RHS Right-hand side
RTD Resistance temperature detector
STP Standard temperature pressure
T/C or TC Thermocouple
TD Turndown (ratio)
TR/Tx Transmitter
US Ultrasonic/United States
UUT Unit under test
WC Water cut
WLR Water in liquid ratio
WRT With respect to

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CHAPTER II

HEAD TYPE AND VARIABLE AREA FLOW METERING

Chapter Outline

1.0.0 HEAD TYPE FLOW MEASUREMENT: GENERAL DISCUSSION

In this section, flow metering based on differential pressure (DP) /head type measurement techniques, which account for major flow meters (nearly 50% of flow meters), are discussed. Head type measurement requires two sets of devices, namely, a flow element (FE) and a differential pressure transmitter (DPT). Of the various flow elements normally used for head type flow measurement, the *wedge type* is an important one normally used for slurry and difficult fluids. Since it has major use in slurries, detailed discussions on wedge meters are covered in Section 5.0.0 in Chapter VII (not here), where slurry flow is discussed. Although Rotameter does not fall under this category, yet same has been discussed here in this chapter at the end. *What is a head type meter?* A head type or differential-pressure (DP) meter works on the principle of a part obstructing the flow in a closed circular pipe to create a difference

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in static pressure between the upstream and downstream sides of the obstructing device—popularly known as a primary device/flow element (FE). In the head type or DP measurement method, the majority of primary devices used in industries are covered under ISO 5167:2003, with various part numbers. Therefore discussions cover the major requirements stipulated in the standard ISO 5167:2003, which is the main international standard for head type flow measurement. Our discussion starts with basic issues in the following subsection.

1. **Topics covered:** The following are the major topics covered for each type of the flow meter in this section.
   - *Description and types of device*;
   - *Features: advantages and disadvantages*;
   - *Sizing (as applicable)*;
   - *Specification sheet*;
   - *Piping and other requirements*;
   - *Installations and mounting*;
   - *Calibration practices*;
   - *Application area*;
   - *General discussion*.
2. **Features of head type flow meters:** Head type flow meters have certain advantages, which have made them popular. However, there are also some disadvantages, such as nonlinearity. Some of the advantages and disadvantages of head type flow meters are listed here.
   - *Advantages:* The following are some of the advantages of head type flow meters:
     - Suitable for liquid, steam, and gases;
     - FEs in head type measurements do not have any moving parts;
     - Performance is easy to understand;
     - Suitable for all process conditions of pressure/temperature and large variations in viscosities;
     - Permanent pressure loss (PPL) in the orifice is high, but in the Dall/Venturi it is low;
     - In large pipe applications they are much cheaper than other types in many cases;
     - Possible for flow calculations in almost all situations;
     - Possible to change ranges;
     - Various tapping styles are supported.
   - *Disadvantages:* Disadvantages of the technique include:
     - Flow is nonlinear—square root relationship with measuring variable DP;
     - Affected by variations in pressure and density;
     - Higher permanent pressure loss, e.g., orifice and some nozzle designs;
     - Some flow element (FEs) require sharp edges (orifices), so it is difficult to use in liquids with solids in them;
     - Discharge coefficients and accuracies are functions of piping layout;
     - Requires a long inlet/outlet section;
     - Expensive, as it requires differential pressure lines, fittings, and sensors;
     - Maintenance can be extensive—experience in installation and maintenance helpful;
     - Aging effect is significant, with degradation due to build ups.

1.1.0 Discussions on Requirements for Flow Elements Covered by ISO 5167 (Part 1):2003

The orifice plate (part 2), flow nozzle (part 3), Venturi (part 4), and cone meters (part 5—2016) are the flow elements covered under the subject standard. Apart from the scope and normative references, the standard covers the definitions of technical terms (such as diameter ratio, pipe Reynolds number, discharge coefficient, isentropic exponent) and measuring principles. These are discussed in detail in Section 2.1.0 of Chapter I. Relevant parts of the standard are discussed in this section. In this text, the relevant article number of the standard is placed within brackets.

1.1.1 GENERAL REQUIREMENTS AS PER ISO 5167-PART 1

1. **Static pressure:** Static pressure is measured at pressure wall tapping/set of interconnected tapping or by carrier ring as applicable.

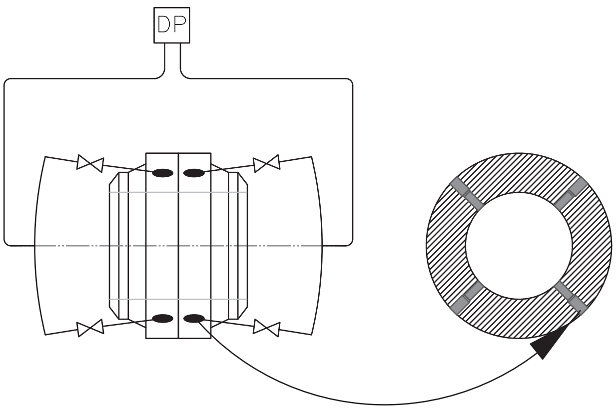


FIGURE II/1.1.1.1-1 Triple-tee connection for static pressure. *Drawing is based on ISO 5167-1:2003.*

Tapping for static pressure is independent from tapping for DP measurement. However, as long as there is no distortion due to double tapping, it is permissible to link simultaneously one pressure tapping with a differential pressure measuring device. A typical triple-tee arrangement is shown in Fig. II/1.1.1.1-1.

2. **Temperature:** The temperature of the fluid is preferably measured downstream of the primary device. The thermo well or pocket should take up the minimum space possible. The distance between it and the flow element shall be at least equal to 5D—as already mentioned in Section 2.1.0 of Chapter I. In the case the fluid is a nonideal gas and the greatest accuracy is required *and* there is a large pressure loss between the upstream pressure tapping and the temperature location downstream of the primary device, then it is necessary to calculate the upstream temperature from the downstream temperature using Joule Thomson coefficient, as described in Section 2.1.0 of Chapter I.
3. **Density:** It is necessary to know the density of the fluid at the upstream pressure tapping; it can either be measured directly or be calculated with the help of the absolute static pressure, absolute temperature, and composition of the fluid at that location.
4. **Primary device:** The primary device referred to in this book is the flow element (FE). The primary devices under this standard (namely, orifice plate/flow nozzle/Venturi and cone meters) should be manufactured, installed, and used as per the applicable part of ISO 5167. For primary devices outside the applicable parts of ISO 5167, the same may be necessary to calibrate the primary device separately under the actual conditions of use. All primary devices (under ISO 5167) should be checked at *intervals* close enough to ensure conformity with the relevant part of ISO 5167 is maintained. Also, primary devices shall be manufactured from *materials* whose coefficient of thermal expansion is known.

1.1.2 GENERAL DISCUSSIONS ON INSTALLATION (ISO 5167-1:2003)

1. **Closed circular pipe:** Primary devices covered under ISO 5167-1:2003 are applicable to fluid flow in *closed circular* pipes.
2. **Full pipe:** The pipe runs *full* at measurement sections.
3. **Straight section:** The FE is fitted between two straight sections (<0.4% from straight line, so, for fitting necessary precaution should be taken for pipe alignment) of closed circular pipes of *constant* diameter with minimum specified lengths without any obstructions or branches, other than those specified in the applicable part of the standard. The minimum upstream/downstream length requirements for each type of FE are guided by the relevant details specified in the applicable part of the standard (for some commonly used fittings).
4. **Pipe bore:** The pipe bore is circular over the entire minimum length of straight pipe. A seamed pipe may be used only if the internal weld bead is parallel to the pipe axis.
5. **Clean pipe:** The interior of the pipe should be clean at all times, after removing readily detachable dirt and/or metallic peeling. The acceptable value of pipe roughness depends

on the primary device—for details, the applicable part of the standard may be referred to.

6. **Drain/vent hole:** The pipe may be provided with drain holes and/or vent holes (with diameter <08D) for the removal of solid deposits and entrained fluids. However, during flow measurement there shall be no flow through drain holes or vent holes, which should not be located near to the primary device.
7. **Meter insulation:** The meter should be insulated in the case of significant temperature differences between the ambient temperature and the temperature of the flowing fluid, in particular, fluids being metered near their critical point where small temperature changes result in major density changes.

1.1.3 FLOW CONDITIONS (ISO 5167-1:2003)

1. **Swirl free:** This occurs when swirl at all points over the pipe cross-section is <2 degrees.
2. Acceptable velocity profile condition at each point across the pipe cross-section occurs when the ratio of the local axial velocity to the maximum axial velocity at the cross-section agrees to within 5%.

1.1.4 UNCERTAINTY (ISO 5167-1:2003)

1. **Definition:** In the standard the uncertainty is defined as "an interval about the result of a measurement that may be expected to encompass approximately 95% of the distribution of values that could reasonably be attributed to the measurand."
2. Under this standard the uncertainty on the measurement of the flow rate shall be calculated whenever a measurement is claimed to be in conformity with the applicable part of ISO 5167. Also, the standard specifies ways to compute uncertainty. According to the standard, uncertainty can be expressed as follows:
   - **Flow rate $q \pm dq$**
   - **Flow rate $(1 \pm \acute{U}_q)$, where $\acute{U}_q = dq/q$**
   - **Flow rate q within $(100\acute{U}_q)\%$**

1.1.5 ANNEXURES OF ISO 5167

The annexure of the said standard deals with a number of issues, for example, annexure A deals with iterative computations formulae; annexure B deals with roughness, some values of the pipe wall have uniform equivalent roughness, k. Selected values have been enumerated in Table II/1.1.5-1.

There are two types of flow-conditioning devices: flow conditioners and flow straighteners. There are three main kinds of flow straighteners. Flow straighteners are devices used to remove or significantly reduce swirl but may not simultaneously produce flow conditions. There are three

TABLE II/1.1.5-1 Pipe Wall Uniform Equivalent Roughness k

Material	Condition	k in mm
Brass, copper, aluminum, plastic, and glass	Smooth without sediment	<0.03
Steel	New, stainless, seamless cold drawn	<0.03
Steel	New, seamless hot drawn/rolled, welded longitudinally	≤0.1
Steel	Slightly rusty	0.1–0.0.2
Steel	Rusty	0.2–0.3
Steel	Encrusted	0.5–2
Steel	Galvanized	0.13
Cast iron	New	0.25
Cast iron	Rusty	1.0–1.5
Cast iron	Encrusted	>1.5
Asbestos cement	Coated/noncoated new/(normal)	<0.03
Asbestos cement	Coated/noncoated new	<0.05

kinds of flow straighteners covered in ISO 5167-1:2003, for example. Like flow straighteners, flow conditioners are also used for flow straightening and they redistribute the velocity profile for better accuracy. According to the standard, "a flow conditioner is a device which, in addition to meeting the requirements of removing or significantly reducing swirl, is designed to redistribute the velocity profile…" All these are discussed in detail in Chapter XI, along with other flow measurement accessories and computing units. In this standard the following flow straighteners and flow conditions are described:

1. **The following flow straighteners are covered in this standard:**
   - The tube bundle flow straighteners;
   - The AMCA straighteners;
   - The Étoile straighteners.
2. **The following flow conditioners are covered in this standard:**
   - The Gallagher flow conditioner;
   - NOVA's design of K-Lab perforated plate flow conditioner;
   - The NEL (Spearman) flow conditioner;
   - Sprenkle conditioner;
   - Zanker flow conditioner;
   - Zanker flow conditioner plate.

1.2.0 Differential Pressure Range Selections

Depending on the process conditions and flow measurement requirements, the DP range is chosen. However, 0–25 kPa is the most common differential pressure range for orifices, Venturi tubes, and flow nozzles because it is high enough to minimize errors due to liquid density differences in the connecting lines to the differential pressure sensor or in seal chambers, condensing chambers, and so on, caused by temperature differences [1]. Also, the majority of DP devices show maximum accuracy near this range. Most differential pressure–responsive devices develop their maximum accuracy in or near this range, and permanent pressure loss is within an acceptable limit. This is a suggested range; however, the actual DP range should be decided based on actual process conditions.

1.3.0 Flow Pulsation and Noise

Differential pressure pulses of short duration ($\leq$1 s) variation in differential pressure developed from a head-type flow meter form fluctuations in flow from reciprocating pumps and compressors. These are also developed due to the random velocities discussed earlier; turbulent flow causes variations in DP even at a constant flow rate. These two factors account for flow pulsation and noise and are responsible for errors in measurement. Random velocity in turbulent flow is the main factor behind flow noise as such velocities are random and do not have any particular pattern. Errors in DP will result in corresponding errors in flow measurement. For normal use, one form or another of "damping" in devices responsive to differential pressure is adequate [1].

1.4.0 Multiple Leakage Points in Installation

In head type flow measurement, flow element is used for flow measurement and, normally, connections to secondary instruments are done with the help of an impulse pipe. With such a measurement arrangement, there is the chance of leakage at different points, such as the nipple to socket connection point, the connection point at tees, the connection to the valve manifold, etc. Whenever continuous welding is used, many of such leakage points can be eliminated. However, this may not be practicable because often it is necessary to take out transmitters, etc. In the case of an integral orifice or integral orifice meter assembly, such probabilities are much lower, as there may not be any impulse line connection.

So far, discussions have been about the standard for head type flow measurement. There are some other head type flow measurement primary elements, which are covered in this section. The specific details of head type flow elements are now discussed. The discussions begin with the most popular flow element, the orifice plate.

2.0.0 ORIFICE PLATE

Of the various types of head flow meters, the orifice plate is the most common. This is basically a machined metal plate with a round hole or orifice (see Fig. I/3.1.1-1), through which fluids flow. The integral metal tab, often referred to as the tongue, where details of the plate size, thickness, serial number, etc. are embossed, facilitates orifice installation. Orifice plates cover a wide range of applications of fluid and operating conditions. Orifice plates offer acceptable uncertainties at comparatively lower cost.

2.1.0 Orifice Plate Description and Features

Guidance for size, shape, and manufacturing tolerances of orifice plates in measurement applications have been well elaborated by the international standardization organizations, namely ISO, AGA, ASME, BS, and others. There are other types of orifice plates, also such as the restriction orifice (RO). ROs have not been well covered for sizing and designing by the above-mentioned standardization organizations. ROs are often exposed to severe flow conditions associated with large pressure reductions and the related fluid conditions caused by liquids flashing to a gas, cavitations, and sonic (choked) flow.

2.1.1 DESCRIPTION AND FEATURES

The orifice plate is manufactured from sheet metal. It is a flat circular plate with an outer diameter greater than the inner diameter of the process pipe into which it is to be fitted. A circular/segmental hole is drilled into it, this is the orifice.

1. **General description and construction details:** The thickness of the plate from which it is manufactured should be >5.0 mm. The coefficient of discharge C_d for the orifice plate, already discussed in Chapter I, is a function of the location/position of the pressure taps, the ratio of the diameter (d) of the orifice to the inside diameter of the pipe (D) (i.e., beta) d/D, the Reynolds number in the pipe line Re, and the thickness of the orifice plate. Each coefficient of discharge applies to the Reynolds number at which it is calculated. Depending on the type, the upstream edge of the orifice is normally sharp and square. The flatness of the plate along any diameter should be within 1% of the dam height given by (D − d)/2 [2]. The following are general requirements.
   - *Thickness of measuring orifice plate:* As guided by the line pressure, temperature, and application. Generalized guidelines are given in Table II/2.1.1.1-1.
   - *Materials:* As per process fluid. A commonly used material is ASTM A240 316/316L. However, depending on the application, different materials are also used. Commonly used materials for various parts of orifice plate assembly by standard manufacturers are listed in Table II/2.1.1.1-2 (this is indicative only).
2. **Classification of orifice plates:** There are a number of ways in which orifice plates can be classified. They can be classified by function and/or use.
   - *Functional division:* There are mainly four types of orifice plates. These are:
     - Measuring orifice plate;
     - Integral orifice;
     - Senior orifice;
     - Restriction orifice.

       These divisions are not strictly accurate; other than the restriction orifice (RO), all the other types are deployed for measurement purposes. Senior and integral orifice plates are intentionally kept separate from measuring orifices,

TABLE II/2.1.1.1-1 Orifice Thickness (Figure Within Bracket is in Inches)

Orifice thickness	3 mm (0.12)	6 mm (0.24)	10 mm (0.4)
Pipe size in mm	25–250 (1–10)	300–600 (12–24)	600–1000 (24–40)

TABLE II/2.1.1.1-2 Materials Used in Orifice Assembly: Standard Abbreviations for Material Specifications Have Been Used

Purpose	Materials (Normally Used by Standard Manufacturers)
Orifice plate	SS304, SS316, SS316L, 321 SS, HastelloyC, Alloy 825; Alloy C276; Titanium; Alloy 625; 22Cr Duplex stainless steels; 25Cr Super Duplex stainless steels; 6 Mo stainless steel; 90/10 Cu/Ni, PTFE, Monel, PP, PVC,PTFE, coated or clad with PP/HDPE/PTFE.
Flange/carrier ring	A105/SS304/SS316/SS316L/CS SS400, SF440A, or PVC
Gasket	CAF/SS Spiral Wound + CAF/PTFE/Teflon/PVC/Rubber, graphite compound, pure graphite (high temperature/pressure)
Studs and nuts	ASTM A193 Gr B/ASTM A194 Cl 2H A193 B16/A194 C14
Pressure tapping	STPG370, SUS304, or SUS316

as they have special purposes and uses, as well as construction differences.

3. **Types of measuring orifice:** From a construction point of view orifice plates for measurement can be divided into the following:
   - *Concentric orifice:* As the name implies, this has its hole or orifice concentric with the main thin circular plate. Concentric orifice plates represent the majority of plates used in all orifice-based devices. They must have an upstream edge that is very sharp and square. The thickness and material are guided by the flow conditions and the fluid that it has to handle. There are a number of varieties:
     - Concentric square edge: These are applied for measurement of flow of clean, low-viscosity liquids, gases, and dry steam at Reynolds numbers in the turbulent regime. The bore is sharp-edged on the inlet and parallel or chamfered on the outlet, based on the beta ratio and thickness. Depending on the design conditions it can offer up to ±0.5% full-scale division (FSD) accuracy. Details are available in Fig. I/3.1.1-1 (middle top row and bottom).
     - Concentric conical: As shown in Fig. II/2.1.1.3-1, concentric conical entry orifice plates have a bore with a conical inlet section and a parallel outlet section. This type of orifice plate design can maintain accuracy even at low Reynolds numbers and can be used to measure the flow of low-density gases and/or clean liquids at high viscosity. These can offer an accuracy of 2% FSD and are available in various sizes from 25 to 600 mm.
     - Concentric quarter circle: These types of orifice plates have a bore with an inlet in the form of a radius [3]. Other than this, they have flow-measuring capability very similar to concentric conical entry orifice plates. They have a slightly lower accuracy of 2.5% FSD. These are also available in sizes from 25 to 600 mm. A typical concentric quarter circle orifice has been depicted in Fig. II/2.1.1.3-1 (middle and right-hand side).

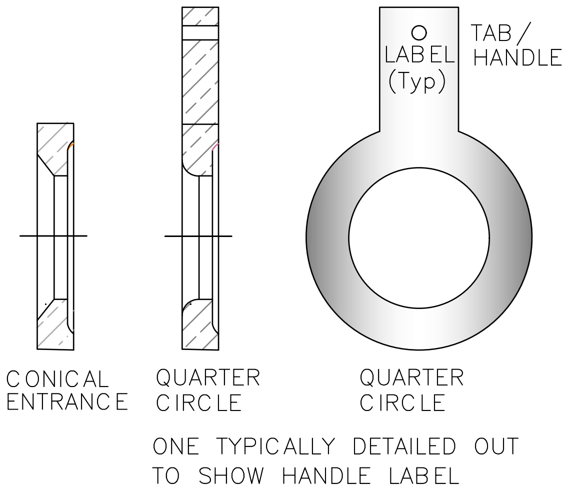


FIGURE II/2.1.1.3-1 Some other orifice types.

The use of eccentric and segmental orifices is preferred when horizontal meter runs are required for fluid flow containing extraneous materials, and there is the possibility of plugging up the concentric orifice.

- *Eccentric orifice:* Eccentric orifices are used for low-viscosity liquids carrying carry solids. These are also used for flow measurement of gas-carrying liquids. A typical eccentric orifice is depicted in Fig. I/3.1.1-1 (top left side). The bore of the eccentric orifice is a circular hole in the plate, adjacent to the pipe wall to give free passage to solids. With the eccentric orifice at the top of the plate, it can measure liquids that carry gas. Eccentric orifice plates are normally available in sizes >100 mm and can offer 2% FSD accuracy. Normally these are used with corner tapping.
- *Segmental:* The bore of segmental orifice plates is in the shape of a segment of a circle with its curved edge adjacent to the pipe as shown in Fig. I/3.1.1-1. Segmental orifice plates are suitable to measure the flow of light slurries and fluids with high concentration of solids. The design of a segmental orifice eliminates the damming of foreign matter and provides more complete drainage than an eccentric orifice plate [4]. When compared with an eccentric orifice it is costlier as well as offering lower accuracy. Therefore, for measurement of liquids with solids or entrained gas, the eccentric type is preferred.

4. **Special orifice types:** Under this category, restriction orifices, integral orifices, and senior orifices are briefly discussed. As stated earlier, the last two types are also used for flow measurements but are shown separately for their specific application areas. Based on their use, various characteristics are discussed for measuring orifices that are applicable for integral orifices, senior orifices, and conditioning orifices.
   - *Restriction orifice:* A restriction orifice (RO) is mainly used to control or restrict flow or for creating a pressure drop in the process medium. The orifice offers a restriction to the process flow and the pressure/head drops from the upstream to the downstream. The device is designed with the intention of a required permanent pressure *loss* by the device. In the case of bypass, a Rotameters restriction orifice (often referred to as a *breakdown* orifice) is used to maintain the desired proportion of the main flow in the bypass line so that by measuring the bypass line flow, the main line flow can be computed. A typical restriction orifice is shown in Fig. II/2.1.1.4-1 which is very much like a measuring orifice, with the

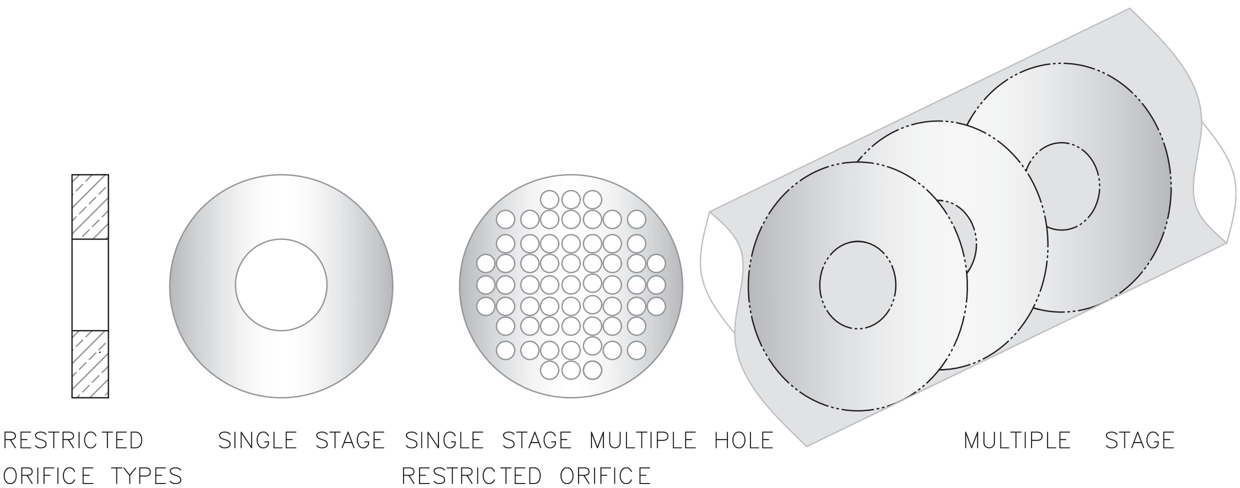


FIGURE II/2.1.1.4-1 Restricted orifice.

only difference being that the design basis is the permanent pressure loss. There are three types of restriction orifice normally used in this process: single stage, single stage multiple holes, and multistage. All three types are shown in Fig. II/2.1.1.4-1.

Based on ΔP, the following equation can be applied:

Critical flow factor

$$F_l = \Delta P/(P_1 - P_v) < 0.7 \qquad \text{(II/2.1.1.4-1)}$$

where P_1 = upstream pressure; P_v = vaporization pressure. The discharge coefficient C_d is dependent on the Reynolds number, and critical flow cannot be created with calculations based on ISO 5167. The ratio of plate thickness t by orifice bore d is very important. If t/d <0.3 critical flow cannot be created. Also, WardSmith has shown theoretically that critical velocity can be obtained, when the discharge coefficient C_d approaches 1. For large drops in pressure more restriction orifice plates in series are used to avoid cavitations and noise.

- *Integral orifice:* A typical integral orifice mounting is shown in Fig. II/2.1.1.4-2, where it is seen that instead of a separate orifice mounting, it is an integral part of the transmitter. This transmitter could be a DPT or multivariable transmitter (MVT).

  The integral orifice assembly includes a process transmitter for measurement of small flow rates. The usefulness of the assembly lies in its ability to economically solve the physical problem of installing an orifice in pipes of 15NB diameter or less. In an integral orifice assembly, the transmitter (DPT/MVT) is mounted either directly or indirectly through an equalizing manifold to the FE assembly. A major application of this kind of assembly includes, but is not limited to, pilot plants, paper plants, and ratio control systems to name a few. Usually these are available with flange connections as shown.
- *Senior orifice:* Changing an orifice plate for inspection and/or replacement is relatively time-consuming and expensive. A senior orifice assembly is an economical solution for such purposes. As shown in Fig. II/2.1.1.4-3 and Fig. II/2.1.1.4-6 (courtesy: Emerson automation solutions), a senior orifice consists of dual chamber fittings, allowing the removal of the orifice plate without interrupting the line flow. In a dual chamber assembly, the lower chamber holding the orifice plate is bolted to the upper chamber, where the orifice plate will be held after removal from the line. Two chambers are isolated with the help of a sliding valve which is opened or closed by a crank/gear shaft. After opening the valve, with the help of another crank (orifice raising crank), an orifice carrier/rack orifice is raised to the upper/top chamber. After raising the orifice plate, the slide valve is closed. Once the valve is closed, the top chamber is depressurized using the depressurizing valve shown in Fig. II/2.1.1.4-3. There is a separate crank for orifice plate removal. Sealing of the chamber is also an important issue. The senior orifice has major applications in oil and gas custody transfer applications.

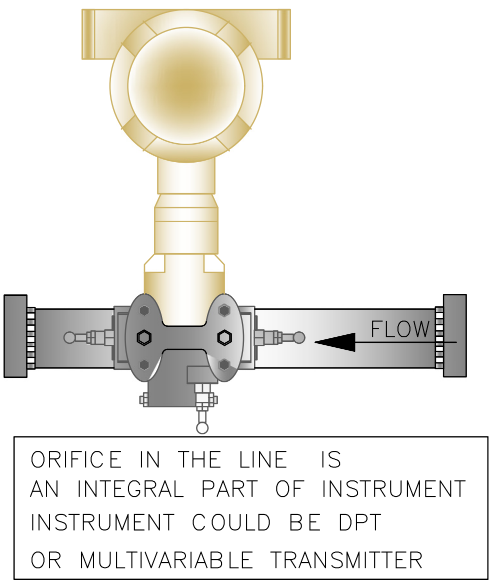


FIGURE II/2.1.1.4-2 Integral orifice.

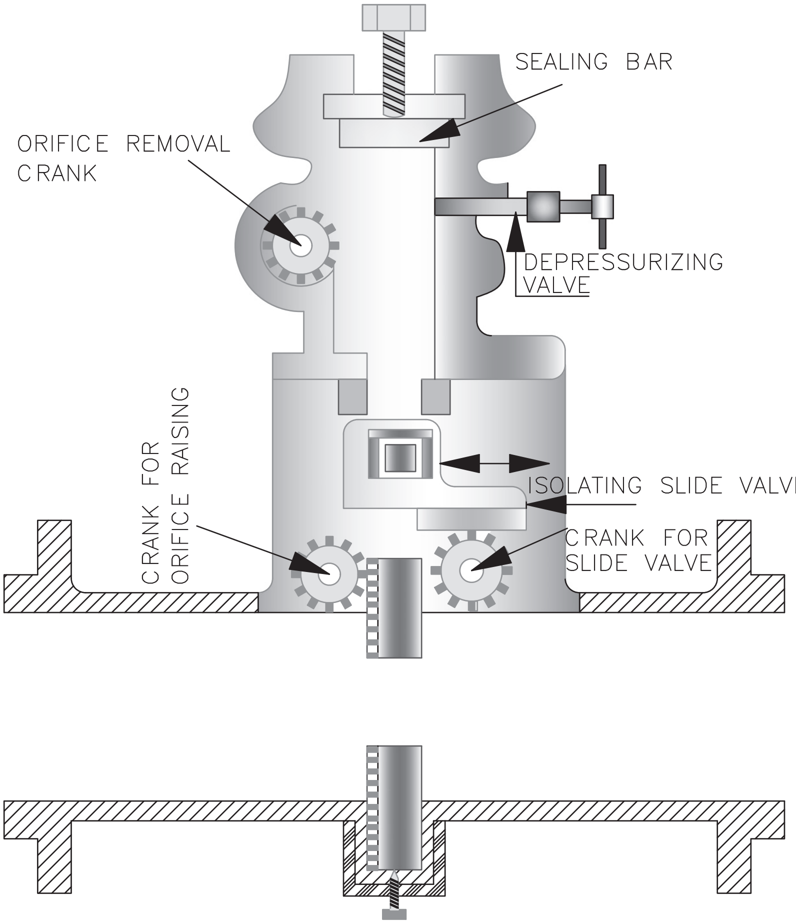


FIGURE II/2.1.1.4-3 Senior orifice (double chamber).

At the end of this section, an image of a Daniel senior orifice fitting is presented; this has been made possible courtesy of Emerson Automation Solutions (e-mail 15th Dec 2016).

- *Conditioning orifice:* Based on Bernoulli's theory, there is another kind of orifice plate referred to as a conditioning orifice. The same standards, such as ISO 5167:2003, AGA Report Number 3, and ASME MFC3M, are also followed here with certain deviations. The conditioning orifice plate varies from the existing orifice plate standards in four ways:
  - Plate thickness;
  - Orifice/beta;
  - Piping requirements;
  - Accuracy.

The major advantages associated with a conditioning orifice include:
  - In this orifice plate, because of its construction, flow conditions itself provide superior performance;
  - Installation in a short straight pipe run, tight-fit applications, 2D standard upstream and downstream straight length requirement;
  - Improved performance in wet gas applications by allowing condensate to pass and preventing the "damming" affect suffered by standard orifice plates.

As shown in Fig. II/2.1.1.4-4, in a conditioning orifice plate, four holes are placed in a circular pattern, with the metal section of the plate in the center of the pipe. Therefore, when flow passes though the conditioning

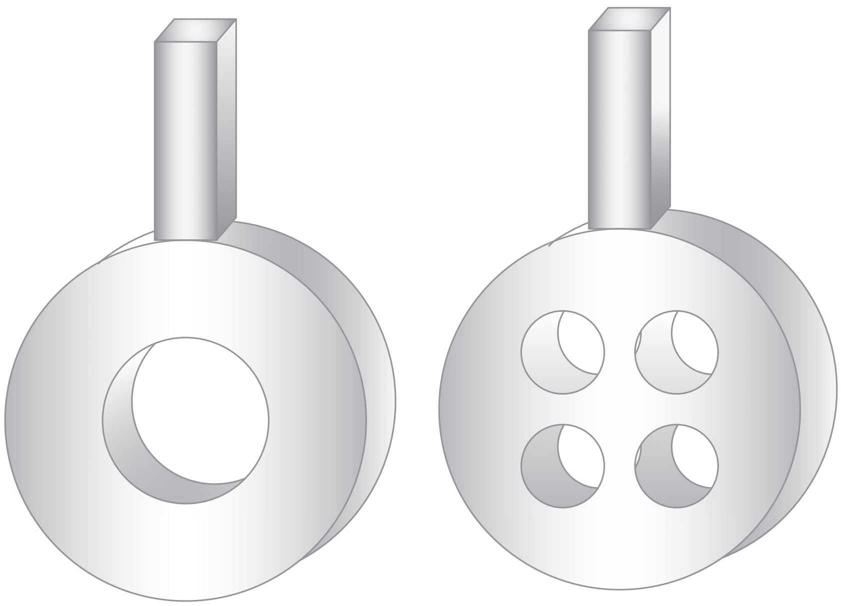


FIGURE II/2.1.1.4-4 Conditioning orifice.

orifice plate, the flow conditions itself, hence there is no requirement for a flow conditioner. Four holes are designed in such a way that the combined area of the four holes in the conditioning orifice is equivalent to the area of a standard orifice of the same beta ratio. A comparison of a conditioning orifice and a standard orifice is presented in Table II/2.1.1.4-1.

The discharge coefficient uncertainty is given in Table II/2.1.1.4-2. It is better to compare this with standards such as ISO 5167:2003 (Figs. II/2.1.1.4-5 and II/2.1.1.4-6).

5. **Advantages of an orifice plate:** There are some distinct advantages to an orifice plate for flow measurement, which is why it is so popular. These are:
   - No moving parts;
   - Robust in construction;
   - Available in a large range of sizes and beta ratios;
   - Very economical;
   - Easier installation;
   - Prices do not change drastically with size;
   - Suitable for most of commonly used fluids;
   - Easier design and implementation.
6. **Limitations of orifice plates:** Orifice plates are very economical for turbulent fluid flow measurement. However, they have a few limitations also.
   - *Permanent pressure loss:* Orifice plates show high permanent pressure loss (PPL) and hence have a higher power requirement.
   - *Accuracy & turn down:* Accuracy is at best within 2%−3%, with turndown maximum 4:1. Accuracy is affected by density, pressure, and viscosity fluctuations.

TABLE II/2.1.1.4-1 Comparison of Conditioning Orifice and Standard Orifice

Characteristic Issues	Conditioning Orifice	Standard Orifice
Orifice bore	Four equal-sized holes placed symmetrically and central metal section	Single central hole
Beta ratio	Two beta ratio 0.4 and 0.65 for high and low flow measurement	This could be any value normally between 0.2 (0.1 ISO) to 0.75
Straight length	Since flow conditions itself, there is no requirement of flow conditioner. So there is less straight length requirement—2D upstream and downstream	Standard orifice plates require significant straight pipes especially in upstream side. This could be reduced by use of flow conditioner
Plate thickness	Thickness is within the specified lengths in standards mentioned above. Only in case of AGA (6″) is it thicker	As per specific standard used
Accuracy	Comparable/better accuracy compared to standard orifice	Standard accuracy
Application	In compact design with transmitter. Hence lower installation cost	Generally as separate loose flow element sometimes with flange assembly. Comparatively higher cost of installation

TABLE II/2.1.1.4-2 Discharge Coefficient Uncertainty (U_{cd} in %)

Beta	0.4	0.65
Reynolds number <10000	$U_{cd} = 1\%$	$U_{cd} = 1.25$
Reynolds number >10000	$U_{cd} = 0.5\%$	$U_{cd} = 0.75\%$

- *Viscosity:* Viscosity limits the measurement range [5].
- *Concentric orifice:* A concentric orifice is not suitable for liquids with dirt or slurry application.
- *Corrosion erosion application:* A sharp edge orifice is not suitable for erosive and corrosive fluids. With correct material selection, the severity could be reduced.
- *Compressible fluid:* $\Delta p/p$ measured in the same unit should be less than 0.25 to avoid error/correction due to changes in density [1].
- *Reynolds number:* An orifice plate is not suitable for Reynolds numbers <10,000.
- *Drain and vent hole:* For entrapped gas in liquid and for dirt, a vent and drain hole can be used but the hole should be <10% of the orifice diameter, otherwise corrections to the flow calculation are necessary. Therefore, prior to design, this should be known. Also, on account of plugging, use of a drain and vent hole is often not recommended, also, as its size increases, accuracy falls.
- *Leakage:* Head type meters with connections to DPT through an impulse line inherently have multiple leakage points. An orifice plate is no exception to this.

***Meter Run Assembly*: For high accuracy flow measurement especially at lower pipe sizes many prefer to use meter run assembly. A meter run assembly comprises an orifice plate with flange connection to main pipeline. As meter run assembly is manufactured as one unit, so various components match with each other. In this arrangement inaccuracies could be avoided. Flange connections to main pipe lines, could be raised face /ring joint type for high pressure applications. Various styles of pressure connections are possible. Meter run assembly could be for flanged assembly, integral orifice assembly. These are normally available for lower line sizes.**

FIGURE II/2.1.1.4-5 Meter run assembly.

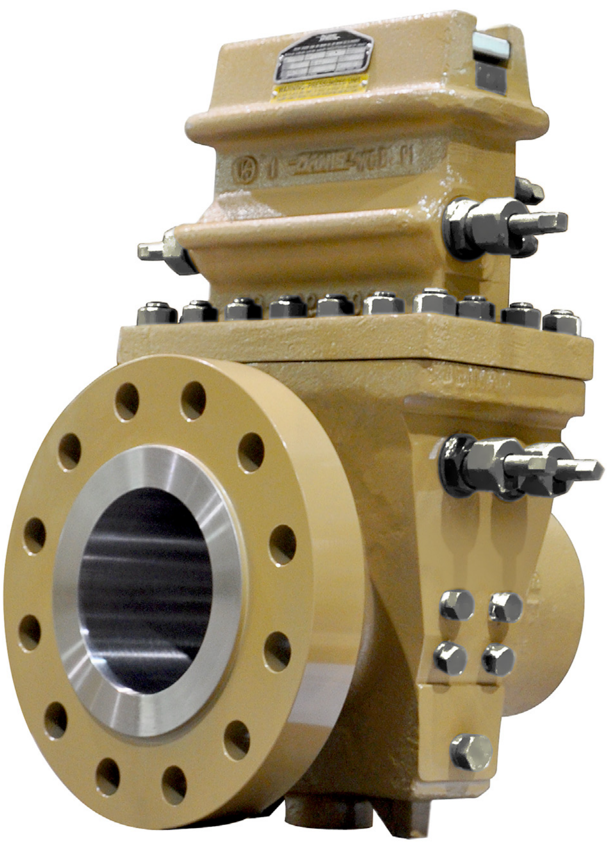


FIGURE II/2.1.1.4-6 Senior orifice fitting. *Daniel Senior Orifice Fitting. Courtesy of Emerson Automation Solutions.*

2.2.0 Tapping Point Installations and Mounting

During the discussions on head type measuring principles in Chapter I and subsequent discussions, it has been shown that orifice flatness, pipe roughness, etc. have effects on measurement accuracy. Similarly, pressure tapping points on pipes, orifice mountings, and installations are very important. Furthermore, these will be highlighted when discussions on standards are discussed in the following subsection. In this subsection, tapping point, tapping point style, mounting details, etc., along with installation details, are covered. The discussion starts with tapping points.

2.2.1 TAPPING STYLES

Single or multiple tapping in a single plane is allowed. From the location of pressure tapping points, in the pipe and/or in the mounting flange, there are five kinds of tapping points available. Normally, the distance to pressure tapping points is measured from (the upstream face of) the orifice plate. Each of these tappings has a specified distance from the orifice for upstream and

downstream (exception: vena contracta) pressure tappings. These tapping styles are as follows:

- Corner tap;
- Flange tap;
- Radius tap (D-D/2);
- Vena contracta tap;
- Pipe tap.

Short discussions on each of these are presented below. This discussion should be read in conjunction with the requirements specified in standard ISO 5167-2:2003 discussed in Section 2.3.2 in this chapter:

1. **Corner tap:** These taps are located immediately adjacent to the plate faces. Corner tappings are located in the corners between the plate and the pipe wall. They may be either single tappings or annular slots. Corner taps are most widely used in Europe for almost all pipe sizes where a small clearance exists in all pipe sizes [1]. Article *5.2.3.3 of ISO 5167-2:2003* has suitable guidelines for the use of this tapping. However, the small clearance mentioned above may be a cause of trouble. Also as the beta ratio increases there will be a rapid change in the discharge coefficient and it may cause instability in measurements for installations with a high beta ratio. For this an upstream tap at D is often used. In the US it is used mainly for pipes <50 mm (2 inches). Corner taps may be used for orifice plates with or without carrier rings. Corner tappings for both these are depicted in Fig. II/2.2.1-1A and B, respectively. Except for a few cases covered in the said standard, flange tappings are more common.
2. **Flange tap:** This design places one pressure tap hole every 25 mm (1 inch) from the upstream and downstream faces of the orifice plate. Being closely located to the face of the

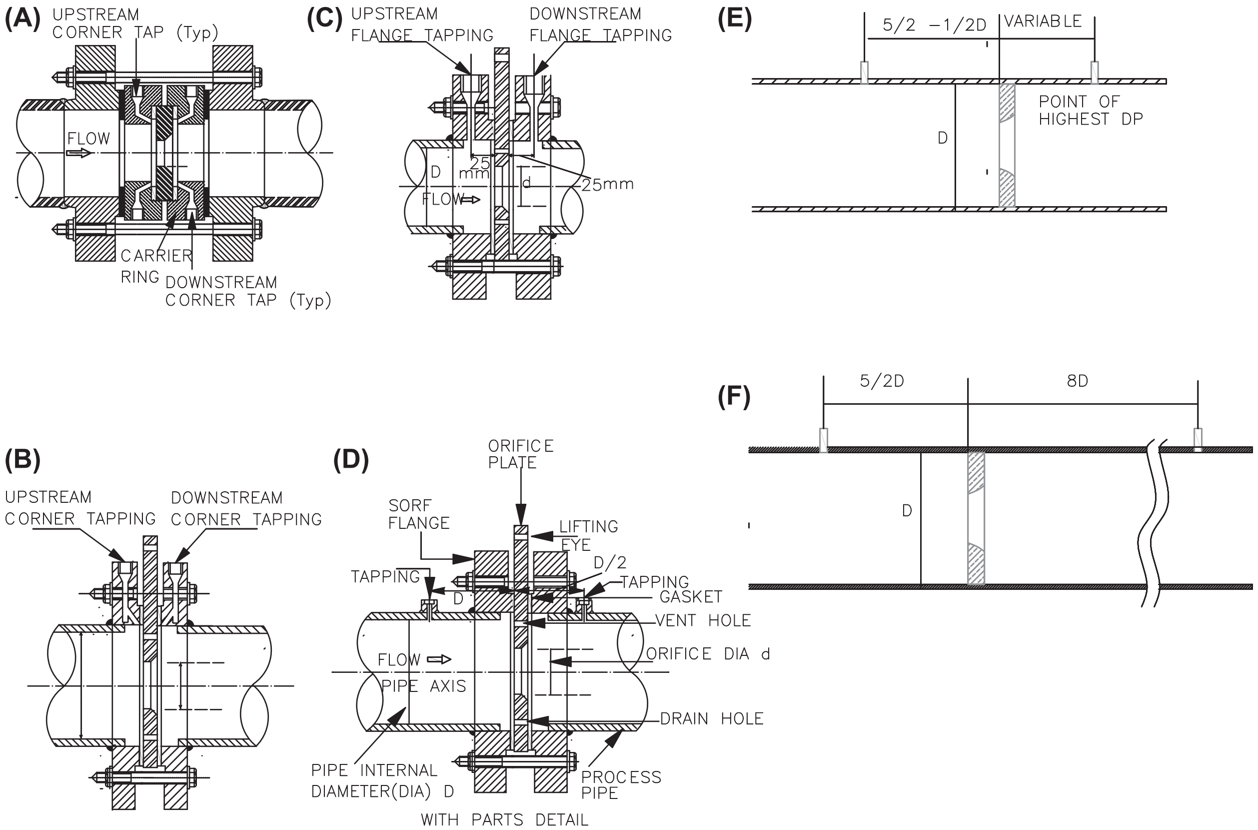


FIGURE II/2.2.1-1 Tapping styles for orifice plate. (A) Corner tap with carrier ring. (B) Corner tap. (C) Flange tap. (D) Radius/D-D/2 tapping. (E) Vena contracta tapping. (F) Pipe tap.

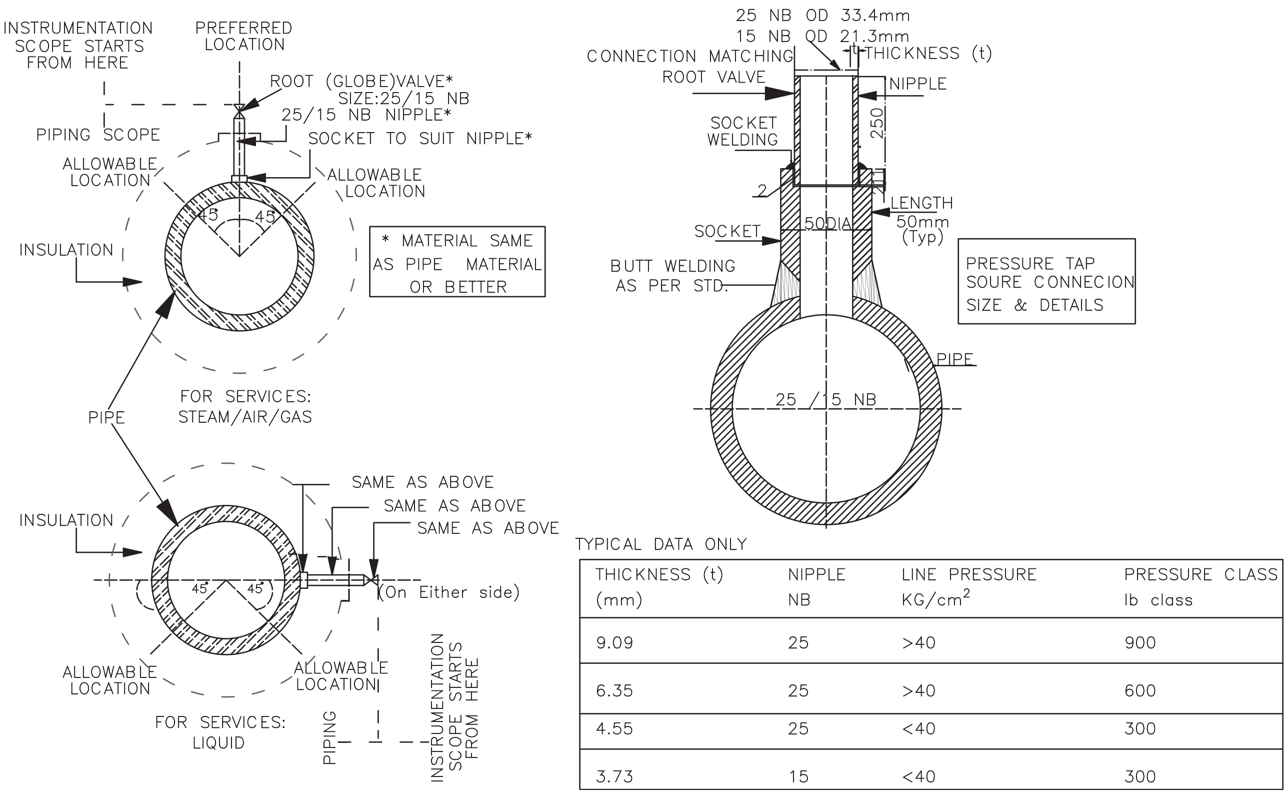
flange, they are easily accessible for inspection. Due to their symmetry, they can be used to measure flow in either direction. In the US these tapping styles are used predominantly for pipe sizes $\geq$50 mm (2 inches). They should not be used in pipe sizes less than 2 inches where the beta ratio is high, and the downstream tap is located in a highly unstable pressure region (as away from vena contracta). This location is helpful for inspection and cleaning up of burrs, weld metal, etc. that may result from installation of a particular type of flange. Fig. II/2.2.1-1C shows flange tapping for an orifice plate. Fig. II/2.2.3-1B shows flange tapping when a carrier ring is used in the orifice plate mounting. Thus flange tapping can be used in both options.

3. **Radius tap:** As the name suggests, the downstream pressure tap is at a one-half pipe diameter (one radius) from the orifice plate to ensure that the tap is not in the unstable region, irrespective of orifice diameter. The upstream pressure tap is located one diameter away from the upstream face of the orifice. Radius taps normally do not vary with beta ratio. Many prefer this arrangement because the downstream pressure tap is located at about the mean position of the vena contracta, and the upstream tap is sufficiently far upstream to be unaffected by distortion of the flow in the immediate vicinity of the orifice. This tapping style is depicted in Fig. II/2.2.1-1D.
4. **Vena contracta tap:** The downstream pressure tap is variable in the sense that it is placed where there will be maximum DP or at the point of minimum pressure downstream, called the vena contracta. As this point, however, variations with the beta ratio or the change of position of the vena contracta with flow rate limit the suitability of these types of taps in practice unless the flow is constant. Also, a tap location too far downstream in the unstable area may result in inconsistent measurement. In the case of small/moderate-sized pipes, the vena contracta is located at the edge/under the flange and locating the tapping point there is not good practice [1]. Here, the upstream pressure tap is D/2—5D/2. This is shown in Fig. II/2.2.1-1E.
5. **Pipe tap:** Fig. II/2.2.1-1F depicts a pipe tap where the upstream and downstream pressure tapping points are located at 2½ pipe diameters (upstream) and 8 pipe diameters (downstream—point of maximum pressure recovery), respectively. This means that both tapping points are located in the region of the fully developed flow, helping in assessing the total drop due to the orifice. This tapping style is also useful for determining the overall pressure losses in the pipeline.

2.2.2 TAPPING DIAMETER AND SOURCE POINT

1. **Tapping diameter:** Even though there is some guidance available in ISO 5167-2:2003 (5.2.2.7), the diameter should be less than 0.13D or 13 mm. In the case of D – D/2 the flange tapping diameter consideration is not critical. More guidance is found in "API MPMS 14.3.2 (API 2000), the tapping diameters must be 9.5 mm (3/8″) for 2 and 3″ pipes and 12.7 mm (1/2″) for 4″ pipes and larger".
2. **Pressure tapping source connection:** Normally pressure tapping for DPTs is the same as that for the pressure taps used. The tapping internal diameter guidelines are available from the standard, based on the process condition thickness of the socket. Usually, the pressure sockets (boss) have diameters of 50 mm (refer to Fig. II/2.2.2-1).

Tapping points in flow element assembly are the socket or boss for the pressure connection to the assembly. However, in practice, for actual physical connections, the nipple, first isolation valve (often referred to as the root valve), etc. are necessary. These are detailed in Fig. II/2.2.2-1. Normally, a globe type valve of suitable size and rating is provided. The materials for the root



THICKNESS (t) (mm)	NIPPLE NB	LINE PRESSURE KG/cm^2	PRESSURE CLASS lb class
9.09	25	>40	900
6.35	25	>40	600
4.55	25	<40	300
3.73	15	<40	300

FIGURE II/2.2.2-1 Tapping orientation and size. *Data from S. Basu, A.K. Debnath, Power Plant Instrumentation and Control Handbook, Elsevier, November 2014. http://store.elsevier.com/Power-Plant-Instrumentation-and-Control-Handbook/Swapan-Basu/isbn-9780128011737/.*

valve nipple as well as the boss/socket are usually selected based on the pipe material or are better suited for the fluid to be handled. Wherever sockets come with the flow element assembly then the main pipe material should be the same or a better suited material for the application. For the thickness of the socket, etc. given in Fig. II/2.2.2-1 is a typical one for a fossil fuel power plant [6], which has to be chosen specifically for the application based on the operating conditions and flowing fluid. Another interesting thing in Fig. II/2.2.2-1 is the scope division between the instrumentation and piping/process. Usually the instrumentation installation work starts after the source/root valve, meaning that the outlet of the root valve is the terminal point for instrumentation. In this the socket weld connections are shown. However, ½″ (other sizes are also possible) NPT/BSP threaded pressure point connections are also quite common. The pressure tapping connections could be flange type, instead of stub/boss and nipple. Therefore, pressure point connections could be socket weld, threaded, or flange types. A typical flange connection (for an orifice plate with corner tapping in the carrier ring and for flange tapping style) is depicted in Fig. II/2.2.2-2 A and B. The advantage of this kind of tapping is that root valves with flange connections can be directly connected.

2.2.3 ORIFICE PLATE MOUNTING

A pair of flanges is used normally for the purpose of orifice mounting. There are several methods available for orifice mounting. The most common include orifice flange assembly, carrier ring, etc. Brief discussions on these are presented in this section.

1. **Orifice flange assembly:** Orifice flange assembly is a very economical solution for

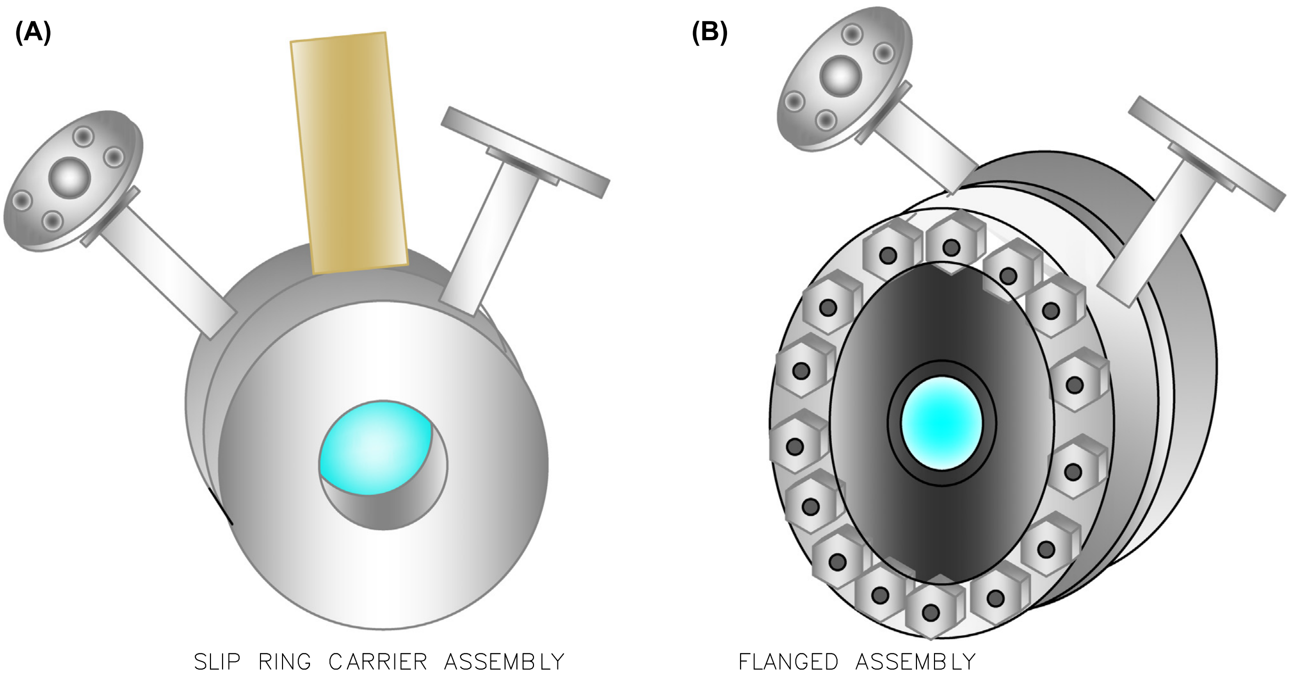


FIGURE II/2.2.2-2 Orifice tapping flange connection. (A) Corner tapping flange connection. (B) Flange tapping flange connection.

flow measurement. There are a few manufacturers who offer integrated assembly as shown in Fig. II/2.2.3-1A. They offer them as an integral part and often offer them with a meter tube as shown by the dotted line in the figure. Normally these are offered with flange tappings. In these assemblies normally raised face flanges are used. These are mainly used for flow measurement of smaller or medium-sized pipes at lower or medium pressure ranges.

2. **Carrier ring:** Apart from flange-mounting, orifice plates are often mounted with the help of a carrier ring placed between a pair of composite flanges. These are used mainly when flanges are not thick enough to provide tappings and also where pipe tapping is not practicable. Often, corner tappings are used with a carrier ring as shown in Fig. II/2.2.1-1A. A detailed cross-section of a typical carrier ring is shown in Fig. II/2.2.3-1B. In this case, flange tapping has been used. There are many configurations of carrier rings. Though not overly popular, there is a type of carrier ring where the orifice is a part of the same construction. Corner tappings are used in this configuration. In this type of configuration it is not possible to make any changes after it is manufactured. In another configuration transmitter mounting pads are typically provided, as shown in Fig. II/2.2.3-1C; also, in many configurations valve manifolds can be mounted on the carrier ring assembly for direct connection. Another kind of carrier ring, as shown in Fig. II/2.2.2-2A, is the slip ring carrier assembly. As shown in the figure, here flanges are normally used as the source connection for pressure tapping. The split ring orifice carrier assembly is a dual-ring orifice carrier with differential pressure tappings and is designed to fit between raised-face flanges [3]. Generally, a concentric square edge orifice is used.
3. **Ring tongue joint (RTJ) plate holder:** The ring tongue joint plate holder is a combination of a plate holder and an orifice plate designed for RTJ flanges as shown in Fig. II/2.2.3-2. The plate holder has two purposes; one function is to hold the orifice plate and the other

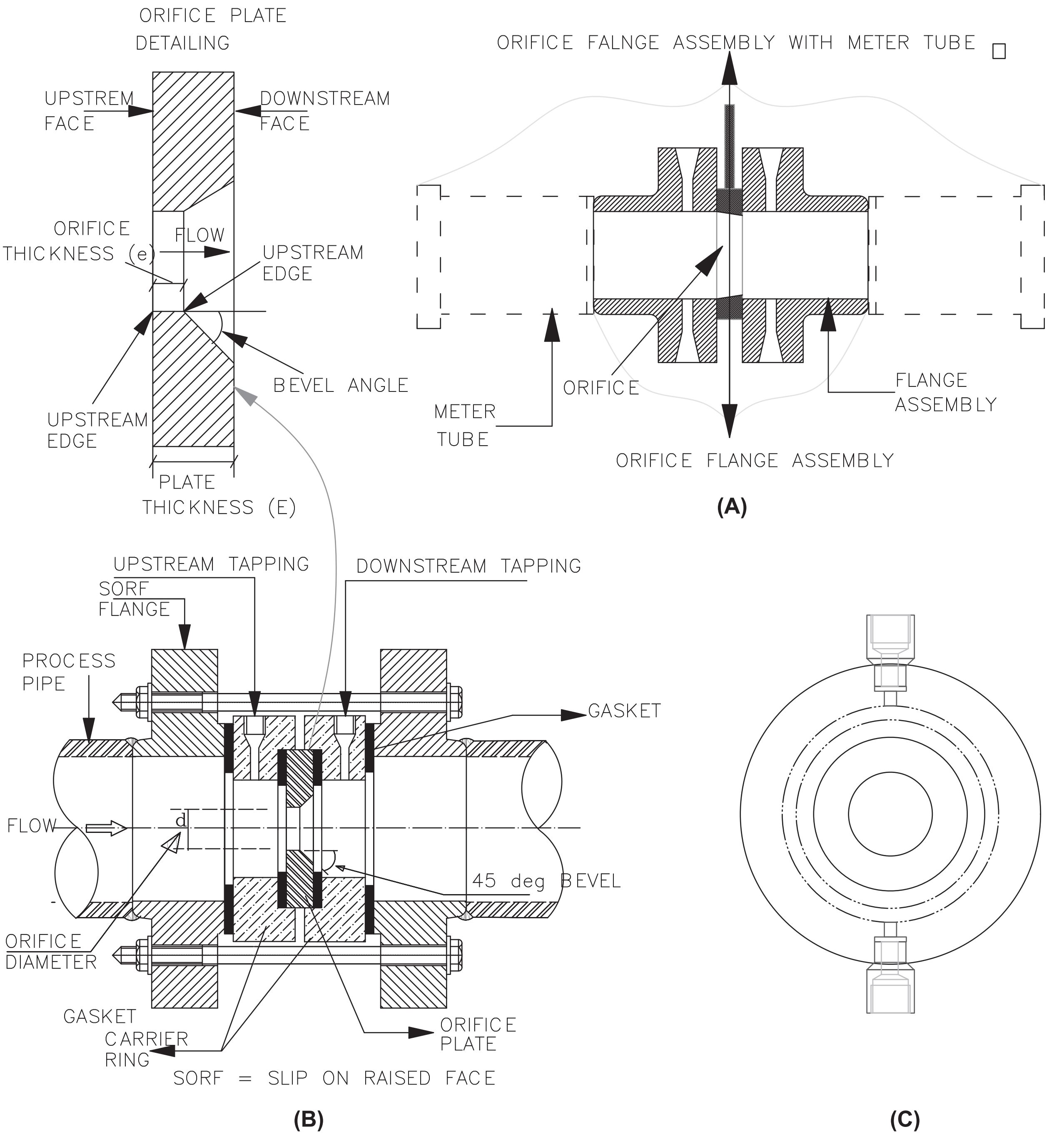


FIGURE II/2.2.3-1 Orifice flange assembly and carrier ring. (A) Orifice flange assembly. (B) Carrier ring with flange tapping. (C) Carrier ring with transmitter mouning pad.

is to act as a gasket to prevent leakage of the process fluid. The plate holder has an oval or octagonal ring for mounting between ring tongue joint flanges. This metallic sealing system is applicable to a fluid of *high* temperature and pressure. Normally the flange tap style is used as a pressure tapping system. An orifice plate is screwed into the plate holder. Generally, the plate holder is of a soft iron material.

4. **Summary of mounting steps:** The following are the basic steps described in a generalized way. There may be minor variations in actual

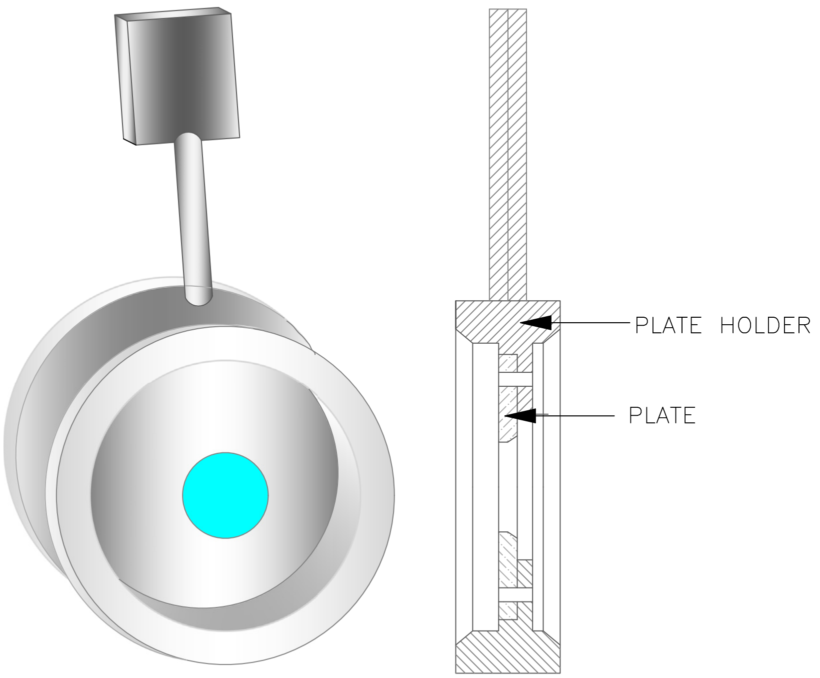


FIGURE II/2.2.3-2 RTJ holder orifice assembly.

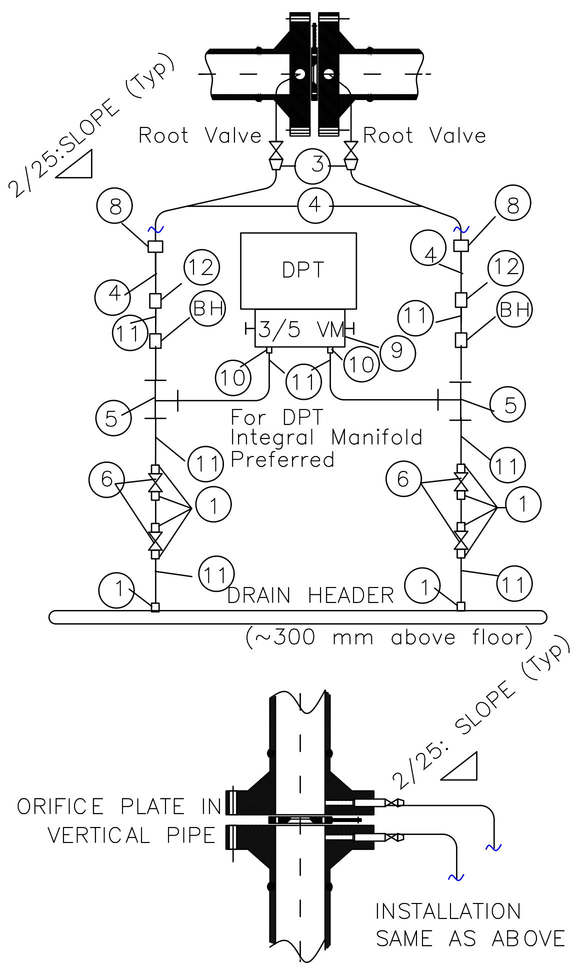
applications; however, manufacturer's recommendations should always be followed.

- Check and confirm the placement of the orifice in the pipe;
- Assure the proper orientation for the intended service;
- Measure the pipe ID at the tapping point;
- Check for leaks;
- The flange is welded to the pipe;
- Ensure cleaning, draining/purging as applicable;
- Ensure that the pipe line is not under pressure and has been drained or purged;
- Loosen all studs and nuts, remove the studs in one flange side;
- Use of jack screw to spread flange;
- Install new plate (or remove existing plate for replacement or inspection);
- Install new gaskets always when installing the plate;
- Assure that the gaskets are trimmed and do not protrude across the face of the orifice plate;
- Release the flange union, replace and tighten studs;
- Orifice plate manufacturing and installation ISO 5167-2:2003 (art: 5.1.2,3) specifies that care should be taken to ensure that due to any stress of deformation the slope of a straight length does not change more than 1% under working conditions.

2.2.4 IMPULSE LINE INSTALLATION

In this section short discussions are provided for impulse line installation, which is part and parcel of head type flow metering, especially for head type flow measurement. Figs. II/2.2.4-1 and II/2.2.4-2 shows the impulse *line* installations for two probable cases, namely the transmitter below and above the source point, respectively. The reader should note the words "impulse line," which can be either an impulse tube or impulse pipe based on the process and owners' philosophy. In many applications, on account of cost, an impulse pipe of carbon/alloy steel is used in place of a stainless pipe/tube.

For impulse lines, a tube is always the preferred choice. As said earlier, on account of the cost of the tube and associated fittings (in tube



DRAWING IS NOT TO SCALE

BILL OF MATERIALS

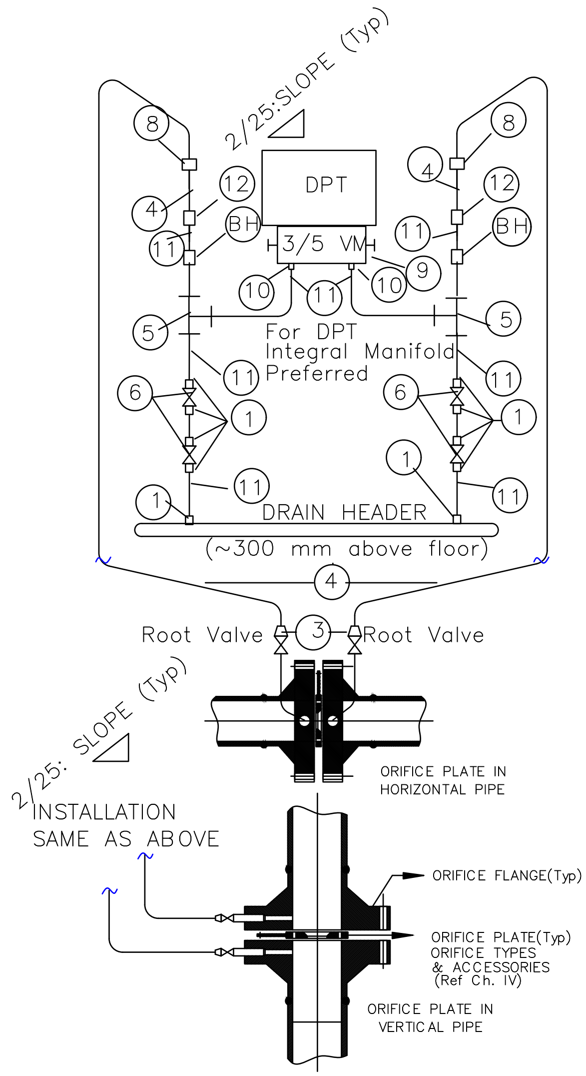
ITEM NO.	ITEM DESCRIPTION
1	SOCKET WELD TUBE CONNECTOR OF SUITABLE SIZE TO MATCH TUBE SIZES. & CONNECTORS.
2	NOT USED
3	3/4" X 1/2" SW REDUCER
4	3/4 / (1/2)" IMPULSE PIPE SCH:40/80/160(Material to suit the application)
5	1/2"/3/4" EQ.TEE for Tube (Inside Enclosure)OR 1/2"/3/4" SW EQ.TEEforPipe(Outside enclosure)
6	3/4"/ (1/2)" Socket Weld GLOBE VALVE
7	NOT USED
8	1/2" / 3/4" PIPE UNION
9	3 OR 5 VALVE MANIFOLD OF SUITABLE MATERIAL (FORGED For Material see CH XII Sec. 2.0)
10	SUITABLE ADAPTER FOR Valve Manifold for tube connection e.g. Male Connector)
11	1/2"/3/4" SS TUBE
12	1/2" / 3/4" PIPE X TUBE UNION

NOTE:

1) BULK HEAD(BH) INTERFACING FIELD & ENCLOSURE AS APPLICABLE TO BE USED. INSIDE ENCLOSURE SS TUBE IS PREFERRED
2) INSTALLATION USING TRANSMITTER ENCLOSURE HAS BEEN DEPICTED HERE. IF, NOT APPLICABLE THEN NECESSARY CHANGES TO BE INCORPORATED.
3) VENT VALVE WITH CAP AS APPLICABLE TO BE USED.
4) FOR STEAM, CONSTANT HEAD UNIT TO BE USED.

FIGURE II/2.2.4-1 Impulse line for orifice 1 (DPT below source point). *DPT*, differential pressure transmitter; *VM*, valve manifold. *Adapted from author's book S. Basu, A.K. Debnath, Power Plant Instrumentation and Control Handbook, Elsevier, November 2014. http://store.elsevier.com/Power-Plant-Instrumentation-and-Control-Handbook/Swapan-Basu/isbn-9780128011737/.*

installations screw and welded connections are not used) separate forged tube fittings and bar stock tube fittings are used and these are comparatively more expensive. However, it is very important to maintain proper tube OD all though out. Imperfection on the tube OD can be potential source of problems in a tubing system. Handling of the tube shall be done very carefully to avoid scratches and protect the finish of the tubes especially in offshore applications. When process transmitters are put into a local instrument enclosure (LIE), it is customary to use SS tubes and fittings inside the LIE. Normally pipes are specified in terms of nominal bore (NB), e.g., X″ NB, where NB stands for nominal bore. NB represents the outer diameter of an imaginary circle within the pipe cross-section [lying normally between the inner (ID) and outer diameters (OD)], but corresponding to each NB there is a fixed OD of the pipe. Therefore, only the NB specification is incomplete. In that case, the complete specification is "X" NB Sch. YY. For each schedule there will be specified thickness. In contrast, a tube specified by XXY indicates



DRAWING IS NOT TO SCALE

ITEM NO.	BILL OF MATERIALS ITEM DESCRIPTION
1	SOCKET WELD TUBE CONNECTOR OF SUITABLE SIZE TO MATCH TUBE SIZES. & CONNECTORS.
2	NOT USED
3	3/4" X 1/2" SW REDUCER
4	3/4 / (1/2) " IMPULSE PIPE SCH:40/80/160(Material to suit the application)
5	1/2"/3/4" EQ.TEE for Tube (Inside Enclosure) OR 1/2"/3/4" SW EQ.TEEforPipe(Outside enclosure)
6	3/4"/ (1/2)" Socket Weld GLOBE VALVE
7	NOT USED
8	1/2" / 3/4" PIPE UNION
9	3 OR 5 VALVE MANIFOLD OF SUITABLE MATERIAL (FORGED For Material see CH XII Sec. 2.0)
10	SUITABLE ADAPTER FOR Valve Manifold for tube connection e.g. Male Connector)
11	1/2"/3/4" SS TUBE
12	1/2" / 3/4" PIPE X TUBE UNION

NOTE:
1) BULK HEAD(BH) INTERFACING FIELD & ENCLOSURE AS APPLICABLE TO BE USED. INSIDE ENCLOSURE SS TUBE IS PREFERRED
2) INSTALLATION USING TRANSMITTER ENCLOSURE HAS BEEN DEPICTED HERE. IF, NOT APPLICABLE THEN NECESSARY CHANGES TO BE INCORPORATED.
3) VENT VALVE WITH CAP AS APPLICABLE TO BE USED.
4) FOR STEAM, CONSTANT HEAD UNIT TO BE USED.

FIGURE II/2.2.4-2 Impulse line for orifice 2 (DPT above source point). *DPT*, differential pressure transmitter; *VM*, valve manifold. *Adapted from author's book S. Basu, A.K. Debnath, Power Plant Instrumentation and Control Handbook, Elsevier, November 2014.* http://store.elsevier.com/Power-Plant-Instrumentation-and-Control-Handbook/Swapan-Basu/isbn-9780128011737/.

the following: the first X represents the tube OD, the second X is for the multiplication symbol, and the Y stands for thickness (e.g., 5/8 × 0.049″ or 12.5 mm × 1.2 mm). These are stated in connection with orifice plate, but applicable for all cases of impulse tubing. For further details Chapter XII of the Power Plant Instrumentation and Control Handbook [6] may be referred to. All these are stated here so that reader can correctly specify impulse pipe/tube as necessary depending on applications. Another issue is that the majority of the fittings are specified in imperial Foot pound second (FPS) so, in the figures under reference same has been specified. For metric units the author needs to convert the same. There will be different considerations for liquid and gas/steam/air measurements and a different approach for each of them.

1. **Valve manifold (VM):** All transmitters (DPTs) are connected to the impulse line via a valve manifold. There are two types of valve manifold for DPTs in flow measurements: three-valve manifold and five-valve manifold,

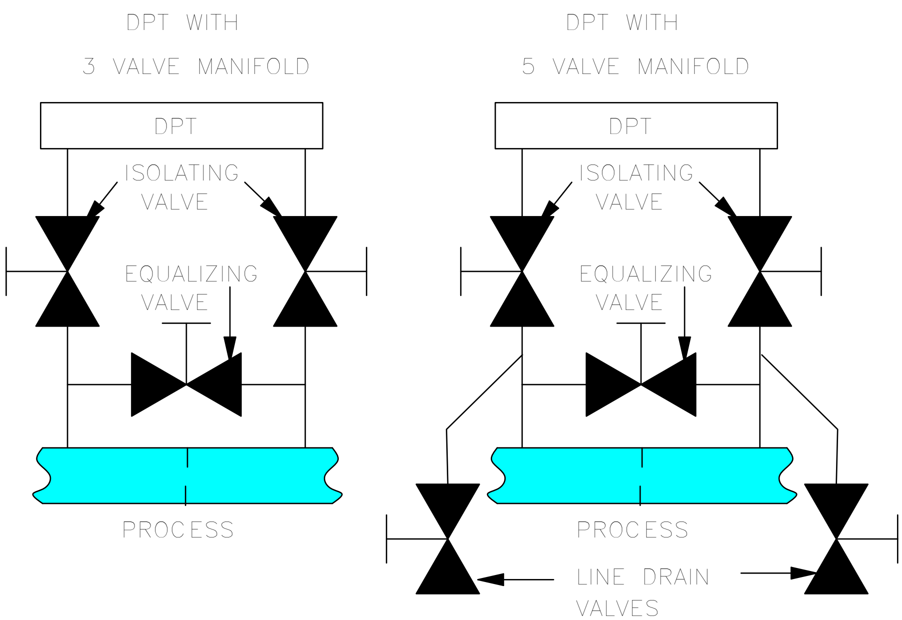


FIGURE II/2.2.4-3 Valve manifold.

as shown in Fig. II/2.2.4-3. In the three-valve manifold these valves are two instrument-isolating valves and one equalizing valve. In the five-valve manifold, an additional two valves may be used for line draining.

2. **Liquid flow measurement:** It is not uncommon that the liquid may have entrapped gas/vapor. Also, there may be dirt that accumulates at the bottom.
   - *Source point connection:* Referring to Fig. II/2.2.2-1 one may notice that tapping is taken from the horizontal side of the pipe. This is done so that entrapped gas/vapor goes to the top and dirt to the bottom in/toward the pipe. However, if it is not possible to have horizontal tapping then around 45° to the horizontal in either side is allowable. To avoid dirt the bottom tap is avoided and for entrapped gas the top tap is avoided. This applies for a horizontal/slight inclined pipe. For a vertical pipe this is not applicable.
   - *Transmitter location:* For measurement with liquid it is always preferable to locate the transmitter below the source point so that there will be a higher positive head available as well as entrapped gas going toward the pipe. In the case that this is not available, then a transmitter can be placed above the source point but the impulse line should be at an elevation slightly above the transmitter level, then making a downward loop connection to the transmitter, as shown in Fig. II/2.2.4-2. Another important issue is the length of impulse line should be as short as possible. This is a function of impulse line diameter and necessary guidelines are available in ISO2186:2007 where not only for liquid service, but for other services are also specified.
   - *Impulse line installation:* After the root valve through a connector the impulse line is connected to the root valve. The impulse line is then taken downward/upward as the case may be. The recommended slope is 80 mm per 1000 mm horizontal run, i.e., a 2/25 gradient. As shown in Figs. II/2.2.4-1 and II/2.2.4-2 the connection to the transmitter is given through a tee so that there is provision for the line drain to drain the manifold (for LIE) or to the instrument drain pipe. This draining is important, especially when after long shutdown an instrument is taken back into service. Another

important issue to be noted that, whenever redundant impulse lines penetrate wall floors etc. there should be some separation (>450 mm) between them.

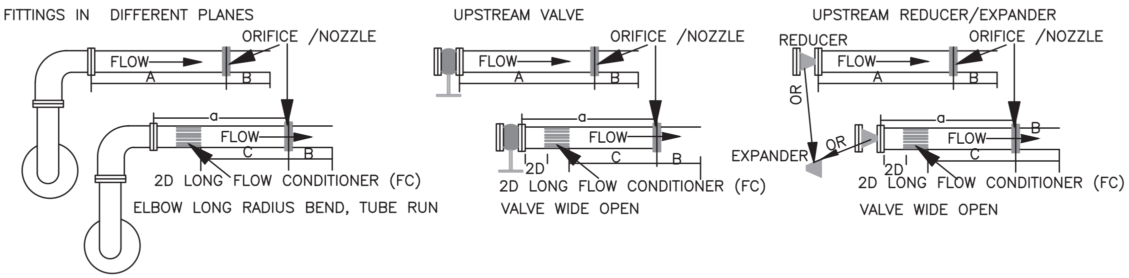
3. **Gas/air/steam service:** It is not uncommon that gas/air/steam may have carried away liquid/condensate. Also, there may be some dust which would accumulate at the bottom. So, like that in case of liquid, there are a number of issues are important for gas/air/steam services also. It is worth noting that impulse line separations, for redundant impulse lines, impulse line distance stated for liquid services are also applicable here.
   - *Source point connection:* Referring to Fig. II/2.2.2-1, one may notice that tapping is taken from the top side of the pipe. This is done so that condensate and dust go to the lower side, in/toward the pipe. However, if it is not possible to perform top tapping then around 45° to the vertical axis on either side is allowable.
   - *Transmitter location:* For measurement with gas/air/steam it is always preferable to locate the transmitter above the source point so that entrapped liquid trickles down to the pipe. In case this is not available, the transmitter can be placed below the source point, but the impulse line should go up a little then take a downward loop to enable a connection to the transmitter as shown in Fig. II/2.2.4-1. This is helpful in eliminating condensate.
   - *Impulse line installation:* After the root valve passes through a connector the impulse line is connected to the root valve. The impulse line is then taken downward/upward as the case may be. Impulse line slope, transmitter connection, and draining as discussed in connection with the liquid is also applicable. This draining is important, especially after a long shutdown when an instrument is taken back into service. In the case of steam, the impulse line is normally filled with water so that high-temperature steam does not come into contact with the transmitter. When the transmitter is below the source point then water in the line is assured, but when the transmitter is above the source point (during shutdowns, etc.), the impulse line water may drain away! In that instance, a constant head unit (CHU) should be used, so that under any circumstances water in the line is assured. If CHU is not used then every time when water in impulse line (above source point) is drained, it is to be filled with water before putting the instrument in service, so as to avoid direct (say) steam at transmitter end.

2.2.5 UPSTREAM/DOWNSTREAM STRAIGHT PIPE REQUIREMENTS

From the discussions in Chapter I (Subsection 1.2.2.6) it is clear that whenever there is an obstruction in any form there will be flow separation and profile disturbance. For head type flow metering, there is a requirement for a straight pipe length upstream and downstream of FEs. There are several standards with different requirements for straight pipe length. Straight length requirements as per ISO 5167-2:2003 are found in tables 3 & 4 of the standard. A brief discussion on the standard has been provided in Section 2.3.0 of this chapter. The standard upstream and downstream straight length requirement based on ASME have been presented (Fig. II/2.2.5-1).

The lengths given are approximate values. Here the values are given for discrete values of d/D (beta ratio). By plotting the lengths against these beta values one can find the lengths for any desired value of beta.

Short discussions of the specific requirements from ISO 51617-2:2003 are given here.



APPROX. DATA FOR ELBOW/TUBE BEND.

d/D	A	a	B	C
0.2	16	10	2	6
0.4	18	10	2+	6
0.5	19.5	10.4	3	6+
0.6	24	11	3.6	7
0.7	30	12	4	7.8
0.75	34	12.2	4	8

LONG RAIDUS BEND DATA SIMILAR SLIGHTLY LESS

APPROX. DATA FOR WIDE OPEN VALVE

d/D	A	a	B	C
0.2	6	10	2	6
0.4	6	10	3	6
0.5	6+	10.2	3+	6+
0.6	8	11	3.6	7
0.7	10	12	4	7.8
0.75	12	12.2	4+	8.2

REGULATING & REDUCING VALVES HAVE HIGHER LENGTHS

APPROX. DATA FOR WIDE OPEN VALVE

d/D	A	a	B	C
0.2	8	10	2	6
0.4	8	10	2.2	6
0.5	8.6	10.2	3	6+
0.6	10.2	11	3.6	6.4
0.7	12	12	3.8	7.7
0.75	13.8	12.2	4	8.2

REGULATING & REDUCING VALVES HAVE HIGHER LENGTHS

FIGURE II/2.2.5-1 Orifice plate straight length requirements. *Based on ASME data. Plot data against beta ratio to get data for any in between beta ratio. All distances are given in terms of pipe id "D." All values are approximate. Refer to the applicable standard.*

2.2.6 PERMANENT PRESSURE LOSS

Permanent pressure loss in an orifice is appreciable when compared with other types such as Venturi and V-cone. Typical PPL for a sharp edge orifice is depicted in Fig. II/2.2.6-1. Here the beta ratio has been shown to be from 0.1 to 0.75 as permitted in ISO 5167.

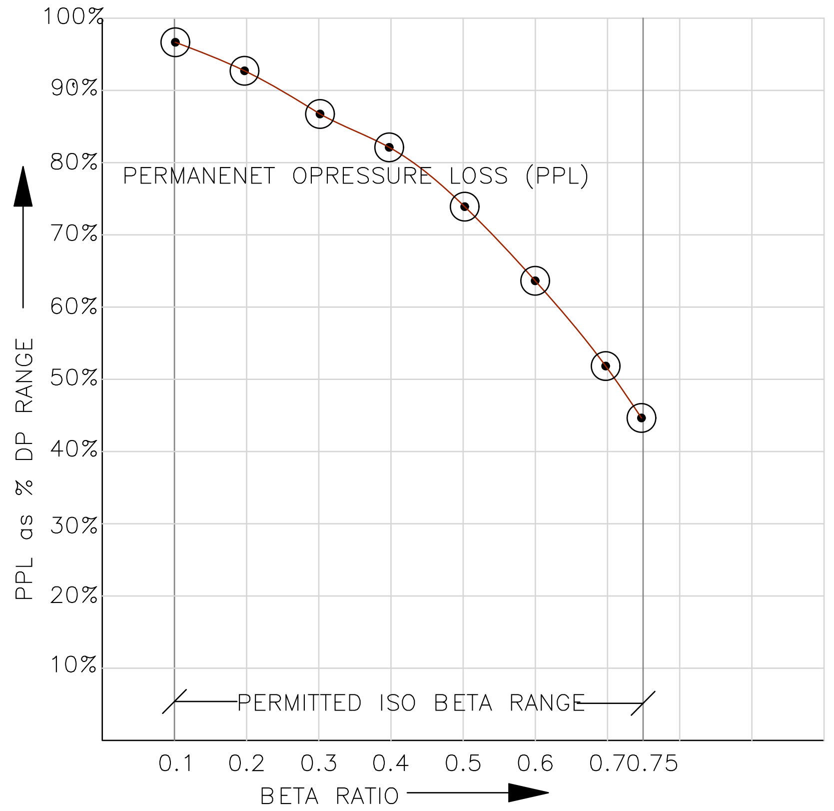


FIGURE II/2.2.6-1 Orifice permanent pressure loss.

2.3.0 Discussions on ISO 5167-2:2003 Standard

Short discussions related to ISO 5167-2:2003 are covered in this section, to enable readers to get to know the basic requirements called for in designing an orifice plate. Here it is important to note that the standard mainly covers standard orifice plates. Apart from ISO 5167-2:2003 there are also other standards, such as ASME, BS AGA Report Number 3, ASME MFC3M, and BS 1042, to name but a few. Internationally, ISO5167 is more commonly used so, therefore discussions here are based mainly on this standard.

General requirements for orifice, flow nozzle, and Venturi and lately cone meters (2016) are also covered under the standard. The general requirements are mainly specified in ISO 5167-1:2003 as already covered in Section 1.1.1 of this chapter. Here discussions will be restricted to the specific requirements for orifice plates.

2.3.1 REQUIREMENTS FOR CONSTRUCTION ISSUES (FIG. II/2.2.3-1)

Issues related to the design and construction of standard orifice plates need to follow the standard in the ways described below. For better understanding it is better to refer to the orifice plate detailing shown in Fig. II/2.2.3-1. This figure clearly shows upstream/downstream faces, upstream/downstream edges, plate and orifice thicknesses, and angle of bevel with respect to flow direction.

1. **Upstream face:** The upstream face should be flat when installed and to check to see that the maximum gap between the plate and straight edge of the pipe ID should be <0.5%.
2. **Downstream face:** This should be flat and parallel but does not call for the same finish as an upstream finish unless it is meant for bidirectional use.
3. **Orifice thickness:** The thickness of the orifice plate should be within 0.005D−0.02D and such value measured at any point along the plate should be within ±0.001D
4. **Plate thickness:** The plate thickness E should be between e and 0.05D where e lies between 0.005D to 0.02D.

   However for 50 mm ≤ D ≤ 64 mm E up to 3.2 mm is acceptable.
5. **Upstream and downstream edge:** The upstream edge should be sharp and without burrs (edge radius $< 4d \times 10^{-4}$). Normally visual inspection will do, except if d is less than 25 mm when it may have to be measured. However, there is no such requirement for the downstream edge as per the standard.
6. **Orifice diameter:** Orifice diameter d < 12.5 mm with beta ratio d/D lying between 0.1 and 0.75 as per the standard. The orifice should be cylindrical and the diameter must be within 0.05% of the mean diameter.
7. **Bidirectional plates:** The plate must not be beveled and the two faces must meet the criteria prescribed in Subsection 2.3.1.5. For radius tapping style there should be two sets of such tapping.

2.3.2 REQUIREMENTS FOR PRESSURE TAPPINGS

Major requirements specified in the standard are discussed below. It is better to read these discussions in conjunction with Section 2.2.1 in this chapter. As per standard there is no restriction on the number of tappings for a single orifice, only that they should be apart by 30 degrees to avoid interference. Various requirements for pressure tapping pertinent to different styles are presented in Table II/2.3.2-1.

TABLE II/2.3.2-1 Pressure Tapping Requirements

Tapping Style	Radius Tapping	Flange	Corner Tapping
Size	Diameter <0.13D and <13 mm		Tapping diameter/annular slot α For *any beta value*
			α = 1–10 mm
			Vapor liquefied gas: α = 4–10 mm OR
			D < 100 mm; α < 2 mm for any beta
Position	Upstream: D	25.4 mm from respective face of orifice	The spacing of tapping center line and respective orifice face equal to ½ of diameter/width of tapping itself
	Downstream: D/2		
Tolerance	Upstream ±10% (0.9–1.1D) Downstream: 0.48–0.52D for beta <0.6; 0.49 to 0.51D for beta >0.6	±0.5 for beta >0.6 & D < 150 mm; ±1 mm for others	*For clean fluid/vapor: beta ≤0.65* α = 0.005–0.03D *beta ≥0.65* α = 0.01–0.02D
Remarks	Tapping center line is at 90±3 degrees		

2.3.3 LIMIT OF USE FOR ORIFICE REYNOLDS NUMBER

The limits of use for the orifice Reynolds number (R_{eD}) are as follows:

For radius tapping: $d \geq 12.5$ mm; $50 \text{ mm} \leq D \leq 1000$ mm;
$R_{eD} > 5000$ for $0.1 \leq \beta \leq 0.56$ and $R_{eD} > 16{,}000\beta^2 D$ for $0.56 < \beta \leq 0.75$.
For flange tapping: $d \geq 12.5$ mm; $50 \text{ mm} \leq D \leq 1000$ mm; for $0.1 \leq \beta \leq 0.75$.
Both $R_{eD} > 5000$ and $R_{eD} > 170\beta^2 D$.

2.3.4 UNCERTAINTIES

1. **Uncertainty of discharge coefficient:** For all types of tappings, when β, D, R_{eD} are known then the uncertainty of C_d is given by:
   $(0.7 - \beta)\%$ for β from 0.1 to <0.2; 0.5% for β from 0.2 to 0.6; $(1.667\beta - 0.5)\%$ for β from 0.6 to 0.75.
2. **Uncertainty of expansibility factor:** Uncertainty is given by $3.5\ (\Delta p/kp_1)\%$ where k is the isentropic exponent (Subsection 2.1.6.3, Chapter I).

2.3.5 PRESSURE LOSS

Pressure loss (Δω) as per the standard is given by:
$\Delta\omega/\Delta p = 1 - \beta^{1.9}$, which is an approximate value after simplification and is accepted in the standard.

2.3.6 STRAIGHT LENGTH REQUIREMENTS FOR INSTALLATION

The straight lengths of upstream and downstream pipes are listed in Tables 3 and 4 of the standards; these may be referred to. Some additional text guidelines are presented below.

General requirements of straight pipe length for installation as per ISO 5167-1:2003 have been discussed in Sections 1.1.2 and 1.1.3. Here the requirements for orifice plates as per standard ISO 5167-2:2003 have been enumerated. In connection with this, the following points should be noted:

1. **Minimum length:** From the tables describing the minimum length requirements it can be seen that minimum length requirements can be reduced by using flow straighteners and

conditioners. The values given in the table (Table 3 of the standards) are minimum requirements.

2. **Measurement:** Straight lengths shall be measured from the downstream end of the curved portion of the nearest (or only) bend or of the tee or the downstream end of the curved or conical portion of the reducer or the expander.
3. **Uncertainty to be added:** Since these are minimum values, any length shorter than those will require adding an uncertainty value as given in column B of the table.
4. **Valve type:** In the case of valves these shall be full bore in full open condition.
5. **Combination fitting:** When there is more than one fitting in the upstream, then a straight length at least equal to 1.5D should be present between fittings one and two. This is in addition to the first straight length requirement in the table.

For further details the standard may be referred to.

2.4.0 Calibration

In this section short discussions are presented on calibration. After acquiring some knowledge about calibration in Section 6.0.0 of Chapter I, generalized discussions will first be presented on liquid and gas calibration methodology. Such discussions are generally applicable for ***flow meters in general***. Subsequently, discussions are presented on calibration systems for orifice plates.

2.4.1 LIQUID FLOW METER CALIBRATION: GENERAL DISCUSSION

As stated earlier this discussion starts with common general methods of flow meter calibration. The liquid flow meter can be calibrated using gravimetric and volumetric methods. The discussion starts with the gravimetric method for flow meter calibration.

1. **Gravity method of calibration:** There are two principal methods of gravimetric liquid flow meter calibration, as shown in Fig. II/2.4.1.1-1, namely the standing-start-and-finish method and the flying-start-and-finish method. A flow meter can be calibrated gravimetrically by weighing the quantity of liquid collected in a vessel. The tare weight and the weight (in air) of the fluid collected are recorded. As the quantity of fluid has to be expressed as mass, the weight has to be corrected for the effect of air buoyancy [7]. To convert the same into volume, mass is divided by a known or measured density or calculated from the process condition under test. To determine the volume, the mass is divided by the density.
   - *Standing-start-and-finish method:* This method, shown in Fig. II/2.4.1.1-1A, is suitable for flow meters used in batch quantity

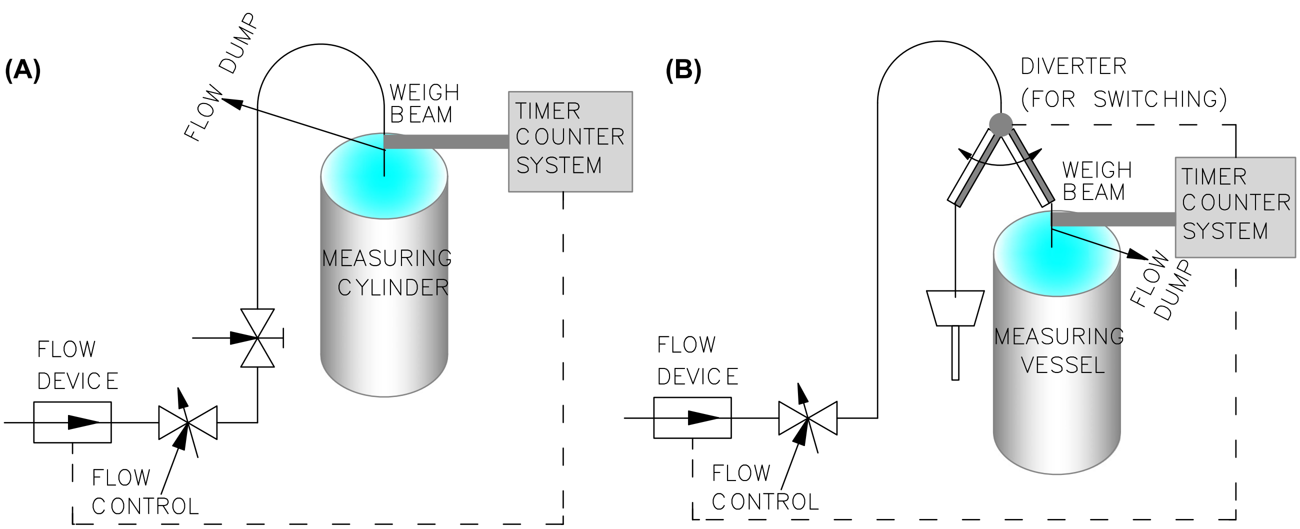


FIGURE II/2.4.1.1-1 Liquid flow meter gravimetric calibration. (A) Standing start finish. (B) Flying start finish.

measurement, i.e., where the quantity passed is of major importance. At first the required flow rate is established in the tank. The flow is then stopped by a fast-acting valve. The container is drained by opening a drain valve which is then closed. The flow is restarted, the container filled, and the flow stopped. The weight of liquid is noted along with the time taken to fill the tank. The reading from the flow meter is also noted. It is also necessary to note the temperature and pressure of the liquid during filling.

- *Flying-start-and-finish method:* This method, shown in Fig. II/2.4.1.1-1B, is used where flow rate measurement is more important than quantity passed as was discussed above. The flying-start-and-finish method is also known as the diverter method. In this method, instead of a stop valve, the diverter between a return to the supply and the collection tank is used. The flow through the flow meter is not stopped but diverted. A switch on the diverter mechanism starts and stops a timer to time the filling of the collection measure and a counter total the pulses from the test device. In this method, the key to accurate measurement is a clean separation between fluid entering the tank and fluid returning to the supply [7].

  Timing error is the main source of uncertainty in the gravity methods discussed.

2. *Volumetric method:* In the volumetric method, a container with calibrated volume is taken for calibration. Normally, this would be a pipette with conical ends to facilitate drainage and to reduce the risk of air entrapment [7]. The calibration can then be carried out either by weighing the water contained in the vessel, or, for larger vessels, using smaller volumetric measures traceable to national standards by weighing methods. Calibration is usually carried out by filling the vessel with a measured weight of water, or by emptying the vessel into a weighing tank.
   - *Calibrated tank:* By diverting to the tank and measuring the flow, in volumetric systems standing start and finish methods are normally used. Drainage time (to empty the tank) is extremely important. When liquid clings to the wall, it takes a significant volume and appreciable time to drain down. It is normal practice therefore to calibrate the tank (along with pipe work) and to establish a consistent drainage time for the calibration. Therefore, the tank has a defined drain time which is marked on the calibration plate and certificate [7]. For this, higher-viscosity liquids gives problematic results, both in terms of accuracy and repeatability due to the unpredictable quantity of liquid left attached to the walls of the tank. Fig. II/2.4.1.2-2A may be referred to for the volumetric tank arrangement discussed.
   - *Correction for expansion/contraction:* Reference volume tanks, and pipe provers, have their volume defined at a reference temperature of 15°C/20°C and pressure of 1.01 bar. Therefore, in the case of volumetric measurement, it is needless to say that there will be a need for a number of corrections due to the expansion and contraction of *both* the standard, and the device being calibrated. Also, the expansion and contraction of the fluid between the standard and the flow meter have to be recognized. Though expansion on account of temperature is the most critical, expansion in a pressurized system should also be taken into account.
   - *Pipe provers:* Pipe provers are more accurate and provide a dynamic volumetric calibration method. They provide a sealed system providing high-accuracy calibrations in situ as well as in laboratories [7]. "Proving" is almost synonymous with calibration but has different implications (refer to Fig. II/2.4.1.2-1). In this connection Section 3.2.0 of Appendix IV may be referenced also.

In the pipe prover system, a length of pipe is fitted with detector switches and the volume between them is known. If a displacer/pig is introduced to the flow, the time the displacer/pig takes to travel between the switches will give a measure of the flow rate. The switches are then used to trigger a pulse counter, so that the totalizing pulses from a flow meter, measuring the pulses per liter (which is referred to as the meter factor) can be determined. The principle of pipe proving is illustrated in Fig. II/2.4.1.2-2B.

Proving: **This term is quite common in oil and gas industries. This is almost synonymous with calibration but in reality it stands to represent calibration with additional task of demonstration or proving accuracy, suitability for the specified purpose and performance against a *few acceptance criteria***

FIGURE II/2.4.1.2-1 Proving.

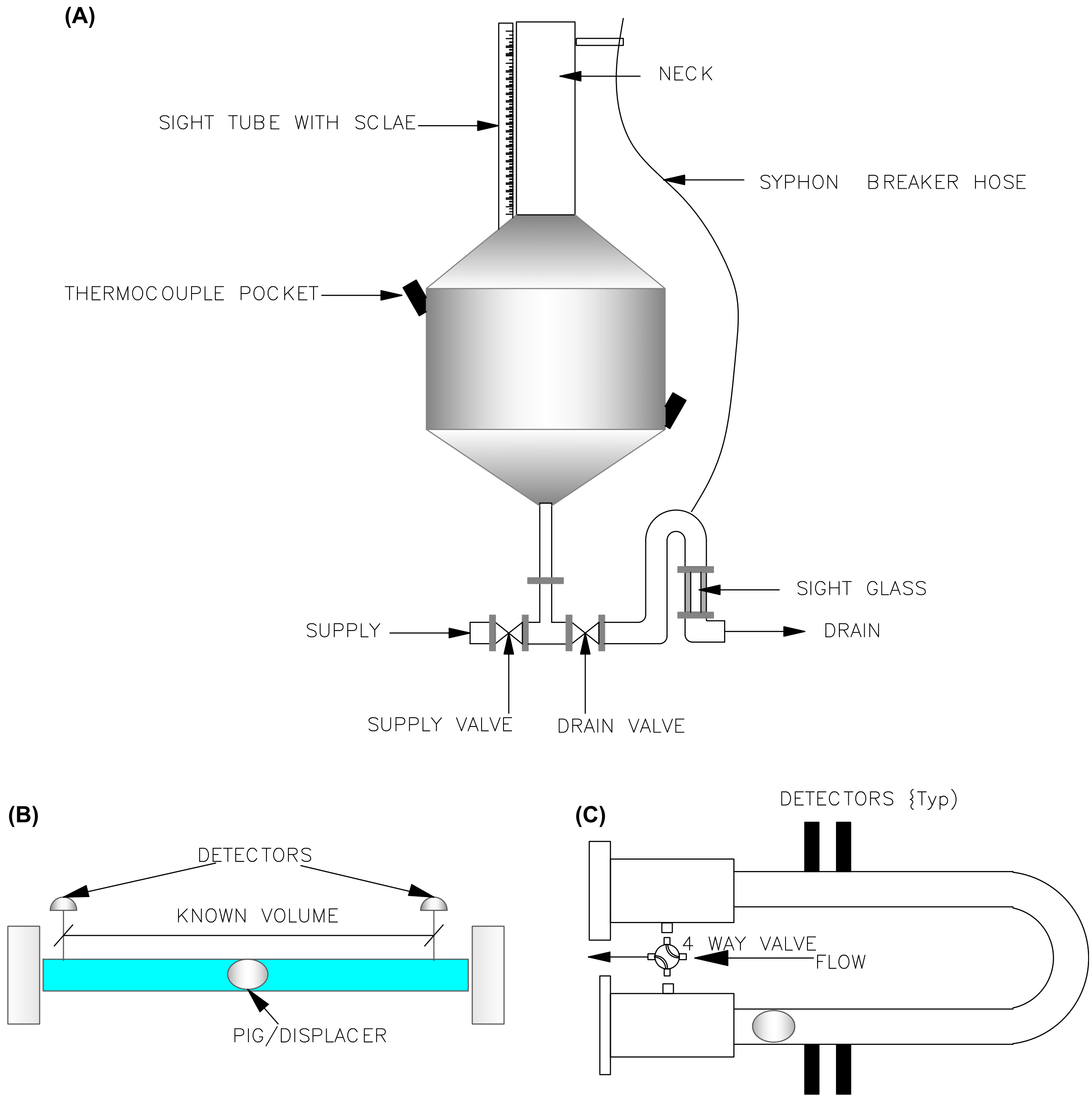


FIGURE II/2.4.1.2-2 Liquid volumetric calibration. (A) Volumetric tank. (B) Pipe proving principle. (C) Bidirectional pipe prover. *Developed based on R. Paton, Calibration and standards in flow measurement, in: Handbook of Measuring System Design, John Wiley & Sons, Ltd, 2005. http://www.nist.gov/pml/div685/pub/upload/sp250-80.pdf, The Calibration of Flow Meters; Good Practice Guide, National Measurement System, TUVNEL. http://www.tuvnel.com/_x90lbm/The_Calibration_of_Flow_Meters.pdf.*

There are a number of ways a pipe prover can be implemented. Of all of them, bidirectional pipe prover is the most popular. The heart of the bidirectional pipe prover is a four-way valve, of very high integrity, that changes the flow path without breaking the flow. As shown in Fig. II/2.4.1.2-2C the sphere is held in special end chambers. These are designed to launch the sphere and absorb the shock of capture [7]. In a bidirectional prover there is a chamber to remove the sphere. There are two sets of detector switches at each end for better integrity.

As indicated above, there are a number of types of orifice plates and associated accessories. In order to help the reader to use the same these are presented in tabular form. The unit of specification is very important for calculation. All units should be specified as per standard to be used, and if necessary, one may have to convert the unit as per the standard to be used. In the following table SI/CGS units are given.

2.4.2 GAS FLOW METER CALIBRATION: GENERAL DISCUSSION

As discussed at the outset of the discussions in Chapter I, the main difference between liquid and gas is the compressibility of gas. Because of the compressibility of gas, any volume measured has to be corrected to a common or "standard" condition. Volume standards generally take the form of displacement devices very similar to flow meter provers [7]. Gas calibration is done utilizing the principles of the pipe prover. Friction is the main issue here. It is necessary for gas to compress until the pressure difference can overcome the friction. Commonly used systems are the bell prover, piston prover, and soap film burette.

- *Bell prover:* In the bell prover system, as shown in Fig. II/2.4.2-1A, normally used for low-pressure calibration such as domestic flow meters, air is displaced in to the bell, which is calibrated. The gas causes the bell to rise or lower as the bell is filled. Water/oil acts as a seal here.
- *Piston prover:* For low-flow calibration, this prover is used. Mercury seal piston provers use a very light and low-friction displacer in a vertical glass tube. The piston is driven by the gas as it travels upward in the tube with a mercury seal formed in a recess in the piston. The weight of the piston is counterbalanced by an external weight [8]. This prover is depicted in Fig. II/2.4.2-1B.
- *Soap film burette:* The basic principle in this prover is the same as the piston prover, except that the piston is replaced by a soap film. Fig. II/2.4.2-1C may be referred to for the scheme for this type of calibration.

2.4.3 ORIFICE PLATE CALIBRATION

Basically, the accuracy and uncertainty of the orifice plate are derived from calculations. Therefore, precise calculation of the orifice plate is very important. Such calculations are nowadays taken care of by computer applications through an iteration process. Once the calculations are done these are then used for manufacturing and precise machining to achieve the required dimensional details to meet the calculations and standard requirements. The dimensional measurements of the orifice plate are extremely important. Dimensions of orifice plates are measured accurately to ensure suitability of the orifice plate for the application in question. Another important issue is that each orifice plate is designed for a differential pressure range (usually 0–2540 mmwcl), precise calibration of DPT/DP cell is carried out in the flow loop for flow calibration. This means that for standard orifice plate calculation checks, dimensional checks are carried out. For flow calibration, associated DPT/DP cell checks are carried out. This is stated here for orifice plates but is equally applicable for other head type flow elements, e.g., nozzle and Venturi. However, from "Orifice metering of natural gas and other related hydrocarbon fluid–part I" American Gas Association (AGA) report no 3, American Petroleum Institute (API) 14.3 one gets some guidance as indicated in the following paragraph.

For accurate measurement, the flow metering system and adjacent piping should meet the requirements of the relevant, preferably the most stringent, specification of the standard. Deviations

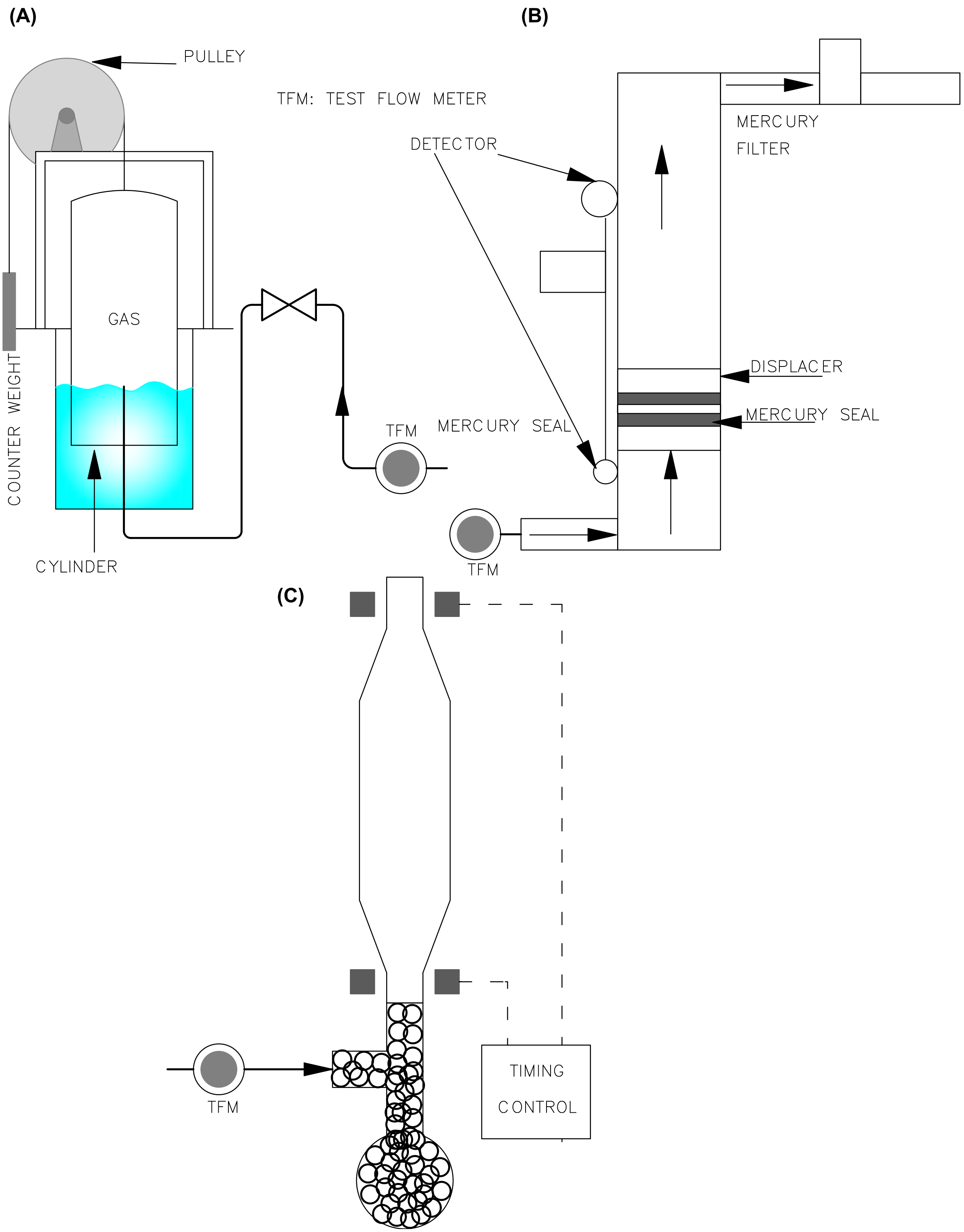


FIGURE II/2.4.2-1 Gas flow meter calibration. (A) Bell prover. (B) Piston prover. (C) Soap film burette.

from the standard's specifications will invalidate the uncertainty statement. In order to assure better accuracy, in situ calibration may be carried out, especially for orifice meters under 2″ (50 mm) nominal pipe size. Calibration of an orifice meter in situ requires a primary mass flow system which may be portable or permanent. A master meter that has been calibrated with a primary mass flow standard can also be used for in situ calibration. The "in situ calibration" should be performed with a primary mass flow system (or master meter) with an overall uncertainty less than the overall uncertainty of q_m of the meter being calibrated.

Whenever an orifice is to be used for a custody transfer issue, i.e., revenue is connected to this then the meter provers discussed above are used. The orifice is placed in series with the meter prover. In such cases the help of specialized agencies is often sought. In all such cases the calibrations are done and traceability is maintained.

Let us now move on to another important issue: orifice specification.

2.5.0 Specification/Data Sheet

For any specific case nonapplicable parts may be deleted, and any additional special features may be indicated under special features listed in the table. While specifying the data, the limits of use of the applicable standard must be considered. The limit of use from ISO 5167:2003 has already been discussed in this section.

2.5.1 MEASURING ORIFICE PLATES

Table II/2.5.1-1 provides the specification for measuring orifice plates. *Flange meter section* orifice plates are available and the length of the meter section depends on the application. Based on the application, the manufacturer should be consulted.

TABLE II/2.5.1-1 Specification for Measuring Orifice Plates

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Type	(a) Concentric: Square edge/ conical/quarter circle, (b) Segmental, (c) Eccentric		User to choose
2	Process fluid	To specify the exact medium and liquid/gas/steam		
3	Flow data	Max/Min/Nor		Nor: Normal
4	Other physical parameters	**(a)** Upstream Abs. Pressure Abs. Max/min/Nor **(b)** Downstream Abs. Pressure Abs. Max/min/Nor **(c)** Temperature Max/min/Nor **(d)** Density **(e)** Viscosity @ temperature **(f)** Reynolds number: for turbulent flow: [**AGA-3: 4000 ISO-5167(2)/ASME MFC-3M(2): 5000 and 170β^2D** Based on flange tapping to see standard] **(g)** gas molar weight **(h)** Specific heat ratio **(i)** Expansionability factor		**1.** To specify OP = operating Max Pr./is dictated by flange rating (pipe schedule) and Max. temp. is guided by material selection and application **2.** Data as applicable to be specified

Continued

TABLE II/2.5.1-1 Specification for Measuring Orifice Plates—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
5	Pipe dimension and materials	Pipe NB and schedule		Pipe schedule is necessary for flange rating
		Pipe internal diameter		
		Standard: From **2 - < 600 mm (*beyond this available manufacturers may be consulted*)**		
		Pipe material: Carbon steel, alloy steel, stainless steel with ASTM code		
6	Tapping style and number of pairs	Corner/flange/radius/pipe	To select	To specify qty
7	Numbers of taps and fittings in supply scope	Quantity in pair (specify)	To specify	
8	Tapping connection	Normally ½″ NPT/BSPT are used others like ½″ socket weld/ flange connections are also available	User to specify based on source connection type selected	
9	Drain/vent hole and size	Drain/vent hole as applicable with size guided by standard		Based on standard user to specify as applicable
10	Mounting style	SORF flange/weld in		
11	Design standard	ISO5167/ISA RP 3.2[a]/DIN 1952/ BS 1042/AGA Rep3.(API 14.3)/ ASME 19.5		User to select and specify
12	Calculation standard	ISO5167/BS 1042/ASME MFC 3M, R.W. Miller, L.K. Spink, AGA—3 others		
13	Carrier ring/RTJ holder/flange assembly	If required, then type for carrier ring. Or to specify RTJ holder and/or flange assembly type. As applicable to be specified		As applicable to specify
	Flange assembly with metering tube			
14	Flange size/ pressure rating/ standard	Nominal size and pressure rating (*150/300/600 lb class*) (normally matching with pipe schedule)/type such as slip on/ weld neckn threaded, socket welded with RF or RTJ facing orifice, etc. standards: *ASME/ ANSI B16.96, BS, JIS, DIN, …*		

Continued

TABLE II/2.5.1-1 Specification for Measuring Orifice Plates—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
15	Orifice plate material	Commonly available materials: SUS304304L, SUS316/316L, SST316Ti DIN 1.4571, Hastelloy C-276 ASTM B575, Monel 400		To choose based on application
		ASTM B127, Duplex, Super Duplex, titanium; Alloy 625; PP, PVC, PTFE coated etc. others.		
16	Carrier ring/ring tongue joint holder	SS400, SF440A, SUS304, SUS316 or PVC soft iron RTJ holder		As above
17	Flange material	ASTM-A105N; ASTM-A350 LF2 ASTM-A182 F5, F9, F11 and F12; stainless steel ASTM-A182 F316(L), F304(L)		Select based on application/ standard. (For other standard equivalent materials)
18	Gasket size/ material	1.6 or 4.5 (spiral wound)/ Material: CAF (IS: 2712 Gr 0/1)/SS spiral wound (+CAF or Grafoil or,PTFE)/6500AC non asbestos/Teflon, graphite compound GF300/pure graphite		Material selection dependent on pressure and temperature rating
19	Nuts/bolts material	ASTM-A194 GR 2H and H8/ASTM −A193 B7 L7		Typically used material
20	Jack screw	ASTM A193 Gr.B7/A-194 Gr.2H		
21	Accessories	Sockets, nipple, root valve, condensate pot		For each qty, material, size, etc. as applicable
22	Testing	Hydro-testing, radiography additional options: Magnetic particle, PMI, gas and water calibrations		As desired to specified. Also to specify required test certificate as applicable
23	Calculated/final data	(a) Differential range (b) Inlet/ outlet velocity (c) Discharge coefficient/uncertainty—standard		In final data sheet by manufacturer
24	Special/additional feature			To specify special feature/ additional feature (if any) here

[a] *ISA RP3.2 provides comprehensive dimensional and tolerance details of FEs.*

2.5.2 RESTRICTION ORIFICE ASSEMBLY

The objective and types of restriction orifice plate have already discussed in Subsection 2.1.1.4. Table II/2.5.2-1 gives the specification sheet for the restriction orifice, however, this should be read in conjunction with Table II/2.5.1-1.

1. **Process fluid:** Refer to Table II/2.5.1-1 point 2;
2. **Flow data:** Refer to Table II/2.5.1-1 point 3;
3. **Other physical parameter:** Refer to Table II/2.5.1-1 point 4 (as applicable);
4. **Pipe dimensions and materials:** Refer to Table II/2.5.1-1 point 5;
5. **Gasket:** Refer to Table II/2.5.1-1 point 18;
6. **Nuts and bolts:** Refer to Table II/2.5.1-1 point 19;
7. **Testing and final data (as applicable):** Refer to Table II/2.5.1-1 point nos. 22 and 23;
8. **Others:** Refer to Table II/2.5.2-1.

2.5.3 INTEGRAL ORIFICE ASSEMBLY

This is a special kind of orifice assembly, which normally comes with a pipe run and hence is often referred to as an integral meter run assembly with flanged connection at two ends. Here the following points should be noted:

1. **Process fluid:** Refer to Table II/2.5.1-1 point 2;
2. **Flow data:** Refer to Table II/2.5.1-1 point 3;
3. **Other physical parameters:** Refer to Table II/2.5.1-1 point 4 (as applicable);
4. **Pipe dimension materials:** Refer to Table II/2.5.1-1 point 5;
5. **Calculation standard:** Refer to Table II/2.5.1-1 point 11;
6. **Design standard:** Refer to Table II/2.5.1-1 Point 12;
7. **Gasket:** Refer to Table II/2.5.1-1 Point 18;

TABLE II/2.5.2-1 Specification Sheet for Restriction Orifice Plate (ref: Section 2.5.2 also)

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Type of restriction	Single stage/single stage multihole/multistage		
2	Permanent pressure loss	Function of pipe size and fluid velocity. 0–150 bar possible	To specify	
3	Plate thickness	Function of PPL and pipe size: 4–40 mm available		Normally selected from PPL versus pipe size curve of manufacturer
4	Noise level	<85 dB		
5	Orifice plate material	Commonly available materials: SUS316/316L. others are available—Manufacturer to be consulted		
6	Flange size/ pressure rating/ standard	Nominal size and pressure rating (*150/300/600 lb class*) (normally matching with pipe schedule)/ type such as slip on/weld neck/ socket welded with RF, etc. standards: *ASME/ANSI B16.96, BS, JIS, DIN*		
7	Special/ additional feature			To specify special feature/ additional feature (if any) here

8. **Nuts/bolts:** Refer to Table II/2.5.1-1 Point 19;
9. **Testing and final data (as applicable):** Refer to Table II/2.5.1-1 point nos. 22 and 23;
10. **Other issues:** Refer to Table II/2.5.3-1.

2.5.4 SENIOR ORIFICE ASSEMBLY

A short specification for the senior orifice assembly, which is mainly used for measurement of natural gas in the oil and gas sector, has been enumerated as Table II/2.5.4-1. Most of these meters are designed as per AGA (report 3).

TABLE II/2.5.3-1 Integral Orifice Assembly: (To Be Read in Conjunction With the Various Points Listed Above)

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Tapping connection	Normally flange connections are used. ½″ Flange for valve manifold		
2	Flange size/ pressure rating/ standard	Nominal size, and pressure rating (*150/300/600 lb class*) (normally matching with pipe schedule)/type such as slip on/weld neck/socket welded with RF etc., standards: *ASME/ANSI B16.96, BS, JIS, DIN, …*		
3	Orifice plate material	Commonly available materials: SUS316/316L. Others are available but not common so manufacturer to be consulted		
4	Flange material	ASTM-A105 N; ASTM-A182 F5, F9, F11, and F12; stainless steel ASTM-A182 F316(L), F304(L)		Select based on application/ standard. (For other standard equivalent materials)
5	Special/ additional feature			To specify special feature/ additional feature (if any) here

TABLE II/2.5.4-1 Senior Orifice Specification

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Purpose	Mainly for measurement of natural gas in oil and gas sector		
2	Orifice standard	ANSI/API 2530 (AGA#3)		
3	Size	Mostly available in 2″ to 14″ sizes are available. However higher sizes even up to 48″ could be possible		
4	Meter tap and specification	Normally two sets of "flange taps" located as per latest versions of		

Continued

TABLE II/2.5.4-1 Senior Orifice Specification—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
		API14.3 (AGA#3). These taps are ½″ NPT connections		
5	Flange details	RF, Weld neck or ring joint flange as per ANSI B16.36 Forged steel-ASTM A105		
6	Operating shaft	Usually single operating shaft		
7	Wench	Speed wench for quick operation of operating shaft		
8	Seal materials	DSC/PTFE seal–TSC/Metal sea-MSC/SNC (API14.3)		
9	Special/additional feature			To specify special feature/ additional feature (if any) here

2.6.0 Orifice Plate Discussions

A general discussion is given on the orifice plate covering with some pertinent points to make the entire section on the orifice plate complete. The discussion starts with orifice plate sizing.

2.6.1 ORIFICE PLATE SIZING CALCULATIONS

In Chapter I, the general flow element calculation was established. Also, the importance of discharge coefficient and its use have been covered. From that equation it can be seen that there could be variation of C_d mainly from beta and d. However, C_d also has variations with other factors including the tapping style. Now we have a closer look at these issues. The discharge coefficient is defined for incompressible fluid. As stated earlier, this establishes the relation between theoretical flow and actual flow. From Eq. I/2.1.4-1A, we get:

$$C(=C_d) = \left\{Qm\cdot\sqrt{(1-\beta 4)}\right\}\Big/\left\{\varepsilon\pi\left(d^2/4\right)\sqrt{2\,\Delta p\rho}\right\}.$$

For compressible fluid the associated factor is expansibility as discussed in Eq. I/2.1.7-1, given by, $= \{Q_m\cdot\sqrt{(1-\beta 4)}\}/\{(\pi d^2/4)\cdot C_d\sqrt{2\,\Delta p\rho 1}\}$

These two factors are most important for flow calculations. In Subsection 2.3.4 of this chapter it can be seen that as per the standard there are some uncertainties to these quantities. Such uncertainties arise because these parameters also depend on the type of tapping and Reynolds number R_{eD}, beta ratio, etc.

1. **Discharge coefficient:** In 1998 Reader–Harris/Gallagher gave the following equation to establish the relationship between Reynolds number and tapping points. This equation for coefficient of discharge C_d (C as per ISO 5167-2:2003) is as follows (Eq. 4 of ISO 5167-2:2003)

$$\begin{aligned}C_d(=C) = {} & 0.5961 + 0.0261\beta^2 - 0.216\beta^8 \\ & + 0.000521\left(10^6\beta/R_{eD}\right)^{0.7} \\ & + (0.0188 + 0.0063A)\beta^{3.5}\left(10^6/R_{eD}\right)^{0.3} \\ & + \left(0.043 + 0.8e^{-10L1} \right.\\ & \left. - 0.123e^{-7L1}\right)(1 - 0.11A)\left(\beta^4/1 - \beta^4\right) \\ & - 0.031\left(M_2' - 0.8M_2'^{1.1}\right)\beta^{1.3}\end{aligned} \qquad \text{(II/2.6.1-1)}$$

For $D < 71.12$ mm; then $\mathbf{+0.11(0.75-\beta)(2.8+D/25.4)}$ is added to Eq. I/2.6.1-1.

In the above equation we can see the relationship between β and R_{eD} with C_d. Also L_1 L'_2 provides the relationship of tapping points with C_d, where ($\beta = d/D$; $R_{eD} = \rho v D/\mu$ and) $L_1 = (l_1/D)$ is the quotient of distance upstream tapping from the upstream face of the orifice and pipe internal diameter.

$L'_2 = (l_2/D)$ is the quotient of distance downstream tapping from the downstream face of the orifice and pipe internal diameter. Here L_2 represents the reference downstream distance from the upstream face.

$$M'_2 = 2L'_2/(1-\beta) \text{ and } A = (19000\,\beta/R_{eD})^{0.8}$$

As per ISO 5167-2:2003 the spacing is given by:

For **corner tap**: $L_1 = L'_2 = 0$; **flange tap**: $L_1 = L'_2 = 25.4/D$ (when D is in mm); **radius tap**: $L_1 = 1$, $L'_2 = 0.47$.

In the standard, values of C_d (=C) are available in tabular form for various R_{eD} and beta values to make the corrections.

In this connection, AGA#3 art 1.7 may be referred to. This article also emphasizes the importance of the empirical formula for C_d. According to this "… the coefficient of discharge can be shown to depend on a number of parameters, the major ones being the Reynolds number(R_{eD}), sensing tap location, meter tube diameter (D), and β ratio: $C_d = f(R_{eD}$, sensing tap location, D. β)."

2. **Expansion factor:** For the expansion factor, the following empirical formula can be adapted:

Expansion factor

$$\varepsilon = 1 - \left(0.351 + 0.256\beta^4\ 0.93\beta^8\right)\left[1 - (P_2/P_1)^{1/\kappa}\right] \quad \text{(II/2.6.1-2)}$$

where kappa (κ) is the entropic coefficient, i.e., specific heat ratio (ref: Chapter I: Subsection 2.1.6.3); kappa = 1.4 for air and other diatomic gas molecules. As per the standard Eq. II/2.6.1-2 is applicable within the limit discussed in this chapter in Section 2.3.3. The above equation (Eq. II/2.6.1-2) can be applied to other gases (than air steam and natural gases) as long as $P_2/P_1 \geq 0.75$ (ISO 5167-2:2003). The standard provides in tabular form the various values of ε in terms of pressure ratio, kappa, etc.

3. **Sizing software:** All these above details are discussed here because there is now available software where all the correction tables are available as part of an iterative algorithm. Based on the requirements, a number of other parameters *in addition to* the basic **flow calculation** and/or **orifice sizing** can be obtained. Also, it is possible that once some of the process parameters and medium are inputted, the software can then calculate other required parameters, e.g., if upstream pressure P_1 and temperature T are specified for gas flow the value for rho is calculated. Standard flow calculators are available for calculating the actual flow rate through the orifice plate flow meter, for measured pressure drop, and can also be used for orifice plate sizing. The following are some of the necessary inputs to the system based on the need for calculation:
   - Flow rate (maximum);
   - Inlet pipe diameter;
   - Orifice diameter;
   - Inlet pressure;
   - Either pressure drop or outlet pressure;
   - Kinematic viscosity or dynamic viscosity;
   - Temperature or density;
   - Flowing fluid gas or liquid;
   - Orifice tap position type.

   Some of the nonselected values can be calculated. In most calculators, unit conversions are possible and/or a number of selections of units are available. Unit selection for parameters is important. Various parameters are automatically calculated, such as the Reynolds number, C_d. Also, these calculators are suitable to be used for commonly used tappings also. The calculation bases

of ISO 5167/AGA3 etc. are often covered, meaning that in most cases the necessary corrections will be covered. As stated initially, these can be used to calculate the actual flow, Reynolds number, inlet outlet velocity, etc.

4. **Uncertainty in flow measurement by orifice:** During the discussions on flow standard ISO 6157 in Section 2.3.4 of this chapter, it was shown that there are uncertainties in the discharge coefficient C_d and this is highly related to the Reynolds number, beta, and pipe ID, etc. These parameters are affected by many other parameters. When there is uncertainty in C_d there will be obviously uncertainty in flow measurement too. Major contributors to measurement uncertainty include:
   - The flow profile and its prediction;
   - Precise definition of fluid properties;
   - Actual fluid properties at flow operating conditions;
   - Precision of empirical equation for discharge coefficient;
   - Manufacturing tolerances in various dimensions of the orifice plate;
   - Secondary instrument uncertainty;
   - Computational assumptions and actual computation.

   Fundamentally, for flow computation we start with a simple basic energy equation, with certain fluid properties. Then to match the actual situation, it is modified empirically to take care of the complex multidimensional viscous fluid-dynamic effects. The pipe Reynolds number is used to correlate the variations in the coefficient of discharge C_d with changes in fluid properties, flow rate, and orifice meter geometry [9]. The actual flow determination is an iterative process described in ISO 5167-1:2003. After iteration twice or thrice, the final C_d is arrived at. Such iterations are carried out to match C_d with R_{eD} as per the standard. This is important to obtain the correct C_d for the flow element. Although at high Reynolds number the effect of viscosity may be insignificant, at low R_{eD} the effect may be significant, and may play a good role in C_d determination. Therefore, the precise relationship between them will ensure better measurement uncertainty. For *compressible* fluids, the *isentropic* exponent is important and this is dependent on temperature (and in some cases pressure also). However, its contribution is not very significant. C_d is empirically computed at steady-state fully developed flow. Therefore, at any deviation from the ideal condition, there will be greater uncertainty in the C_d value, and hence on measurement uncertainty. Wrong installation (mainly in the upstream side) often causes flow profile distortion, with flow fluctuation responsible for the introduction of uncertainty. At times the following issues create difficulties in the precise measurement of flow:
   - Gasket or sealing device recesses and protrusions;
   - Non achievement of dimensional requirements;
   - Tolerance of various geometric dimensions beyond the recommended value in the standard;
   - Nonconformity of flow profile with that predicted;
   - Fluctuations/pulsation of flow, hence DP is measured (which is nonlinear).

   Therefore, all required actions need to be initiated to obtain better measurement accuracy.

   ISA RP 3.2 is quite popular for orifice dimensions and tolerances.

   The discussion on the orifice plate is concluded and we now look at the flow nozzle—another flow element under head type flow measurement.

3.0.0 FLOW NOZZLE

Compared to orifice plates, flow nozzles have a lower pressure drop but are in demand for high-precision manufacturing. In high-pressure/velocity applications, where erosion or cavitations

would wear or damage an orifice plate, flow nozzles are deployed; e.g., high-pressure steam flow measurements in power plants where orifice plates may not be suitable. Flow nozzles can be used for fluids with solid particles. In these cases flow nozzles are installed as an economical solution for flow measurement. There are three common types of flow nozzle. These are: *ISA1932 flow nozzle*—European design, *special Venturi flow nozzle*—*a combination of* the ISA1932 flow nozzle with a divergent outlet like a Venturi, and the long radius/*ASME* flow nozzle. ASME nozzles are shape like a quarter of an ellipse. Again, ASME flow nozzles are of two types. These are given in Table II/3.0.0-1.

TABLE II/3.0.0-1 ASME Nozzle Types and Use

Type	Beta Ratio Range	Geometry	Remarks
High beta nozzle	0.45–0.8	Flattening of quarter ellipse (i.e., higher major axis)	0.25–0.45 both can be used
Low beta nozzle	0.2–0.5	Less flattened (i.e., major axis slightly more than minor axis)	

As indicated earlier, flow nozzles demand precision manufacturing and machining, being a part of the manufacturing process. Therefore, high-precision machining is required for flow nozzle manufacturing. Modern days surface finishes on the order of 6–10 μin [1] are available. Therefore, it is possible to get coefficients with much less uncertainty. Stainless steel, chrome-moly steel, aluminum, and fiber glass are normally used as materials for flow nozzle manufacturing. We now investigate the design and construction details of flow nozzles.

3.1.0 Description of the Construction Details and Features: Flow Nozzles

From the discussions so far, it is clear that, in head type measurement principles, restrictions are put in the fluid flow path to cause a pressure drop, which is related to the flow rate by applying Bernoulli's equation. Flow nozzle is a flow element of that kind, similar to orifice plate. The flow nozzle is used for high-velocity flow measurement, where erosion or cavitations would wear or damage an orifice plate. The flow nozzle has a smooth inlet which results in a higher coefficient of discharge than most other differential meters. This means greater flow capacity when compared to most other flow elements in head type flow measurement, of the same size. A typical flow nozzle with its disposition in a pipe is depicted in Fig. II/3.1.0-1. As already discussed

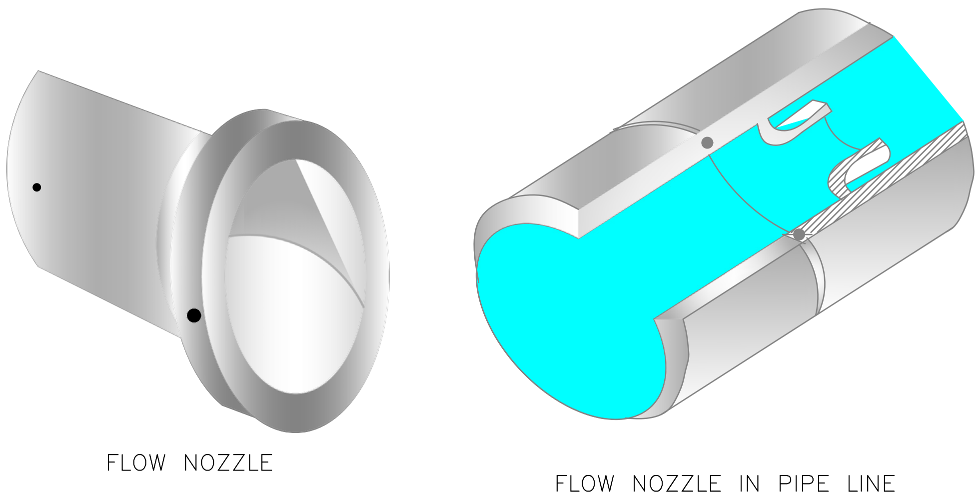


FIGURE II/3.1.0-1 Flow nozzle and flow nozzle in pipe line.

earlier, from a design point of view, flow nozzles can be classified as:

- **ASME MFC-3M flow nozzle**
  - Long radius
  - Short radius;
- **ISA 1932 flow nozzle;**
- **Venturi flow nozzle.**

1. **ASME flow nozzle:** On account of its smooth rounded design, the ASME flow nozzle not only gives a higher discharge coefficient, it is also more effective for sweeping-through of particles in the flow stream, extending product life by reducing wear and potential damage. ASME flow nozzles follow ASME MFC-3M. ASME nozzles offer ± 2% uncertainty of coefficient of discharge. These are used for a beta ratio of 0.2–0.8 in throat with a Reynolds number ranging between $(0.1-2.5) \times 10^6$. One of the most critical points in manufacturing is the beveling of the discharge side of the nozzle. Here the 10 degrees back angle meets the throat bore, the edge must be sharp [1]. During manufacturing special care is taken to meet the design requirements, avoiding out of roundness of the throat. Flow nozzles have an elliptical inlet. The length of the major axis of the elliptical inlet is responsible for nozzles' suitability in a high or low beta ratio. The higher the length of the major axis of the elliptical inlet, the greater its suitability in a higher beta ratio. In this regards, Fig. II/3.1.0-2 may be referenced. In Fig. II/3.1.0-2 various dimensional details are illustrated. These dimensions are in inches (as per standard), here the equivalent mm dimensions are indicated.
2. **ISA 1932 Flow nozzle:** The ISA 1932 nozzle is suitable for high-velocity, nonviscous, erosive flow, which otherwise would wear or damage an orifice plate. The discharge coefficient of the nozzle is such that for same

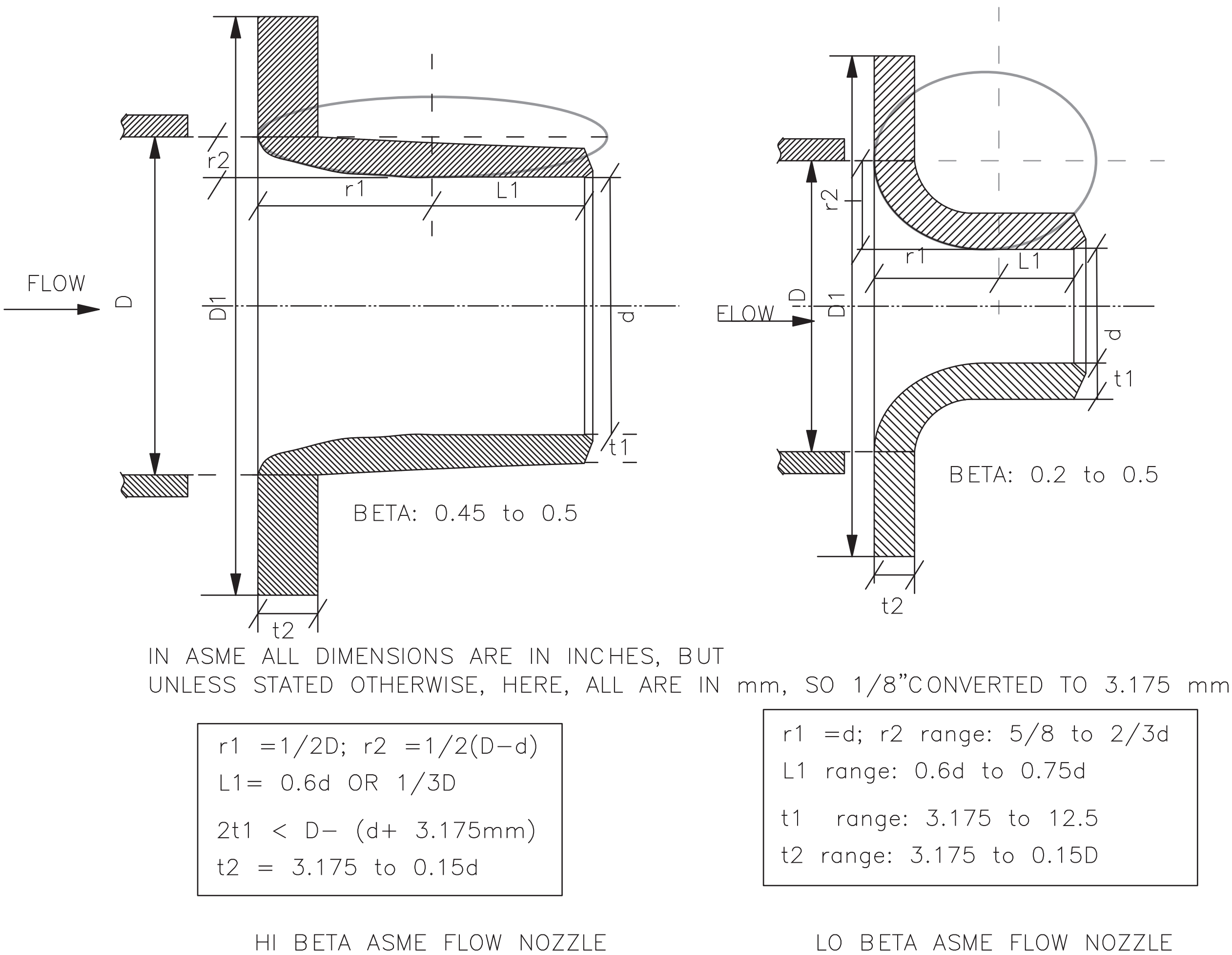


FIGURE II/3.1.0-2 ASME flow nozzle constructional details.

beta ratios it can measure about 55% higher flow when compared with an orifice plate. Similarly, it requires less straight length. Similar to other nozzle types, ISA 1932 nozzles have a smooth inlet leading to a throat section with a sharp discharge. The ISA nozzle consists mainly of three sections, as clearly shown in Fig. II/3.1.0-3 (LHS). These are the flat inlet shown in figure by (A) perpendicular to center line, at the upstream face. This is followed by two convergent sections both inside and outside depicted in the figure by (B) & (C). The final section is the cylindrical indicated in figure by E, outlet throat. For details of ISA nozzle profile parameters A-G, subsection 3.3.1.1 of this chapter may be referenced. ISA 1932 nozzles are available with a carrier ring/flanged assembly. Weld neck mounting is also possible. These are also available as meter run discussed earlier i.e. as an assembly as depicted in Fig. II/2.1.1.4-5. Corner pressure taps are used upstream and downstream of the nozzle. An ISA 1932 flow nozzle in a carrier ring with single taps and/or annular slots is depicted in Fig. II/3.1.0-3 (LHS).

3. **Venturi nozzle:** Venturi nozzles are usually deployed for flow measurements in gases, vapors, and liquids. Normally this is covered by ISO 5167-3:2003. It offers moderate accuracy of <2%. Low-pressure drop is the main characteristic feature of this flow element. The geometrical profile of the Venturi nozzle is symmetric about the axis with a convergent inlet section with a rounded profile, a cylindrical throat section, and a divergent outlet as shown in Fig. II/3.1.0-3. It is normally used for Reynolds numbers ranging between 0.15×10^6 and 2×10^6.
4. **Materials:** Normally flow nozzles are manufactured from SS 316/SS3i6L/SS304/F91/F9 and aluminum and fiberglass. Apart from general structural steel, nonalloy steel C22.8, heat-resistant steel: 16Mo3, 13CrMo45, etc. are a few materials which are also used for flow nozzles. Materials for carrier ring flange, gasket

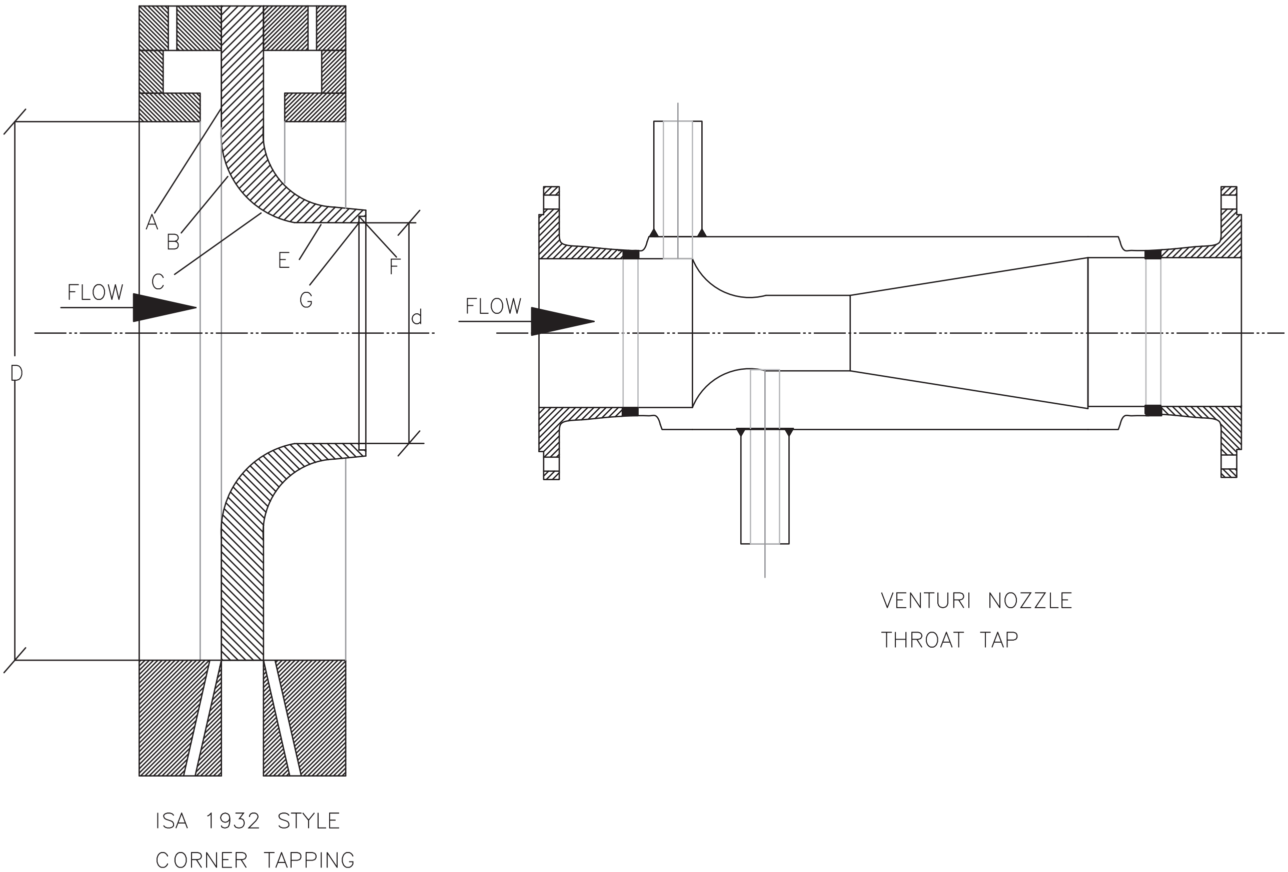


FIGURE II/3.1.0-3 ISA 1932 and Venturi flow nozzle.

stud nuts and bolts, as discussed in connection with the orifice plate, are also applicable here.

5. **Advantages:** Major features and benefits include:
   - *Application:* Widely used for high-pressure high-temperature steam flow measurement (especially in power plant applications);
   - *Velocity:* Flow measurement for flows with high velocity;
   - *Construction:* On account of smooth rounded/elliptical input not damaged by accompanying solid particle lesser erosion hence extended product life;
   - *Moving parts:* No moving parts hence extended product life
   - *Profile:* Flow nozzle profile is inherently robust with minimum maintenance and inspection required;
   - *Damming:* No damming effect;
   - *Cleaning:* Much better seep for debris and liquids.
6. **Disadvantages:** There are a few disadvantages/limitations to flow nozzles:
   - *Installations:* Installations are difficult when compared with orifice plate installations;
   - *Pressure recovery:* Pressure recovery is less than with a Venturi tube;
   - *Shock:* Possibility of pressure shock during recovery.

3.2.0 Tapping Mounting and Installation

There are a number of tappings applicable for flow nozzles. Also, there are several mounting types of low nozzles. These are all discussed here. Fig. II/3.2.0-1 shows both flanged mounting with D-D/2 as well as throat tapping style. In this

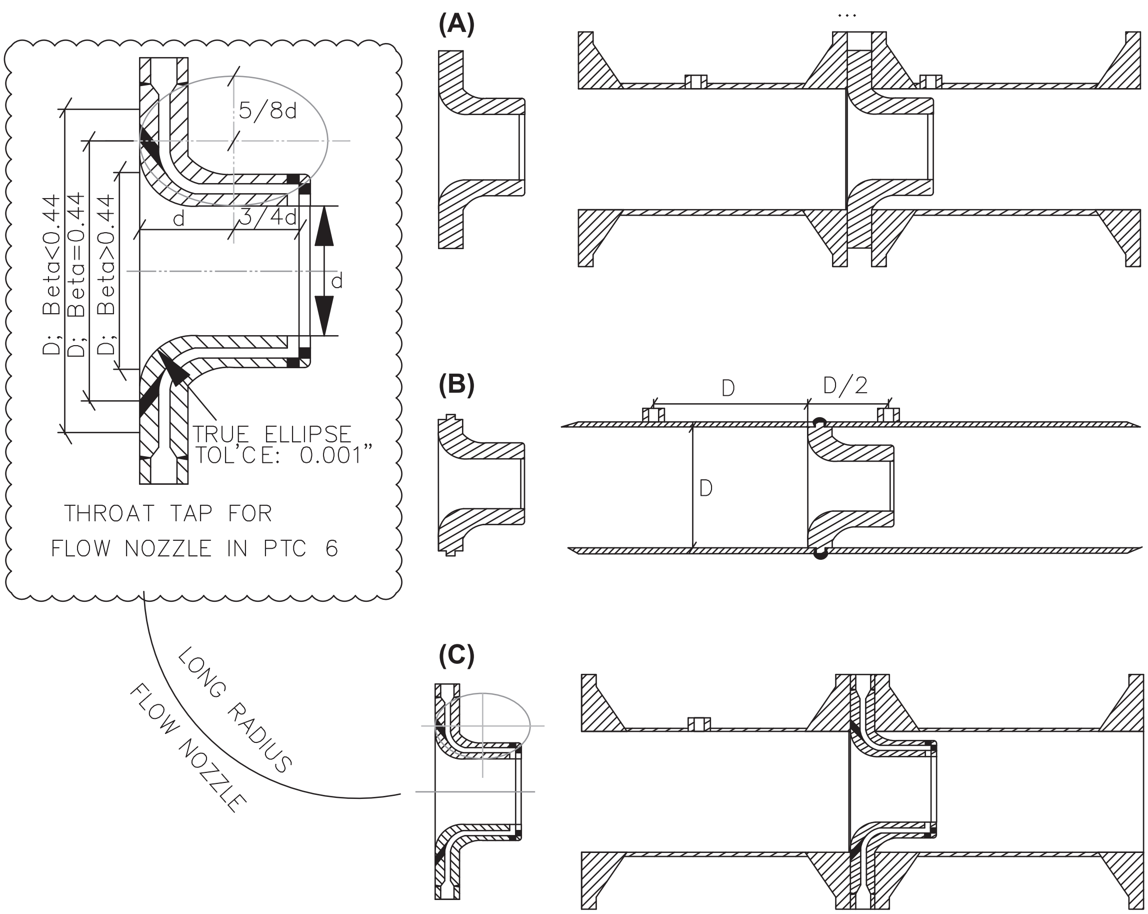
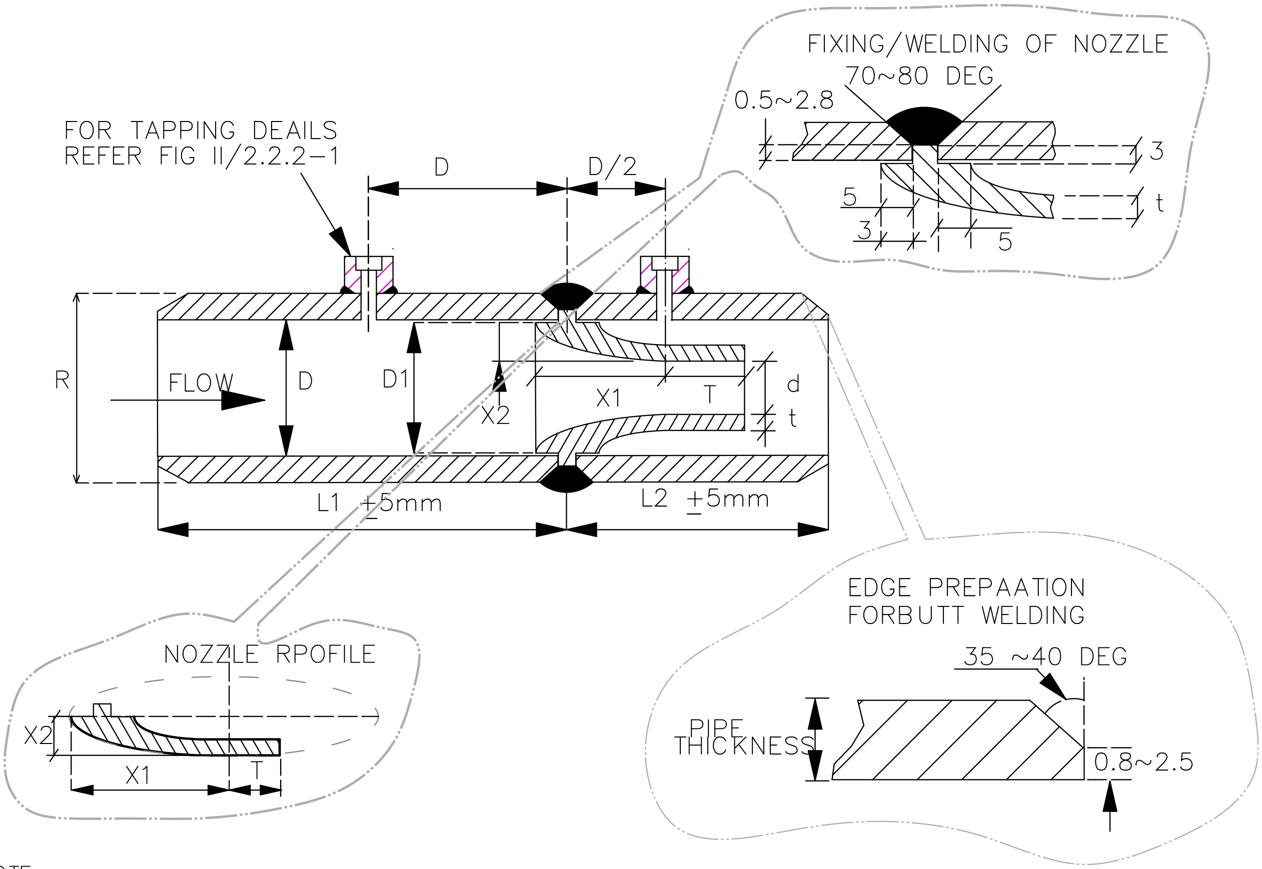


FIGURE II/3.2.0-1 Flow nozzle mounting and tappings. (A) Flange mounting in spool piece/meter run (typical). (B) Weld in mounting and radius tap (D – D/2) in spool piece/meter run (typical). (C) Throat tap flange mounting in spool piece/meter run (typical) long radius nozzle with detailing for PTC 6.



NOTE:

1. NOZZLE DESIGN WOULD BE AS PER RELEVANT STANDARD viz. ISO 5167–3:2003
2. ULTRASONIC TEST WOULD BE CARRIED OUT FOR BUTT WELD JOINTS
3. ALL WELDED JOINTS WILL BE TEST RELIEVED AS PER APPLICABLE CODE.
4. FIGURES ARE NOT IN SCALE; ALL DIMENSIONS ARE IN mm AND TYPICAL IN NATURE.
5. THIS IS SUITABLE FORHIGH PRESSURE AND TEMPERATURE STEAM FLOW APPLICATIONS.

FIGURE II/3.2.0-2 Welded flow nozzle mounting (in steam flow).

figure, throat tapping for ASME PTC 6 has been detailed out separately.

A welded-type flow nozzle arrangement with D-D/2 tapping has been shown in Figs. II/3.2.0-1 and II/3.2.0-2.

3.2.1 TAPPING STYLES

Corner tapping, throat tapping, and radius tapping are common in flow nozzles. Various tapping styles and mounting details are illustrated in figures.

1. **Corner tapping:** Corner tappings are used upstream of the nozzle. Upstream tappings may be either single tapping or annular slots. These tappings are either in the pipe, flanges, or carrier ring. The spacing between the center lines of individual upstream tappings and upstream face may be half a diameter or half of a width of the tappings themselves. The downstream tapping may be a corner tapping or at a place guided by the standard discussed later. There is no restriction on the minimum width of tappings, only as directed by the requirements that these are not blocked quickly. The upstream and downstream tappings may be in different planes. ISA 1932 flow nozzles often use corner tappings. Corner tapping is depicted in Fig. II/3.1.0-3 (LHS).

2. **Radius tapping:** As the name implies, here the pressure tappings are:
   - *Upstream tap:* D (+0.2D/−0.1D) from inlet face of nozzle (ISO 5167-3:2003);
   - *Downstream tap:* O.5D ± 0.01D from inlet face of nozzle (ISO 5167-3:2003).

   Radius tappings are used for various mounting styles and for ASME nozzles. Generally this tapping is independent of beta ratio. ASME MFC-3M type flow nozzles also have radius taps. They also have throat type pressure taps. Fig. II/3.2.0-1 (center) should be referred to.
3. **Throat tapping:** This type of tapping is quite common in ASME nozzles. Throat tap is a typical requirement of ASME PTC 6 for performance measurements. A typical throat type as per ASME PTC 6 has been detailed in Fig. II/3.2.0-1. It also shows the relation between the pipe internal diameter (D) with beta ratio. In throat tap the upstream tappings are located at D distance from the inlet face of the flow nozzle and the downstream tap is located at the throat. In ASME PTC 6 four pairs of such tappings may be used. Long radius throat-tap nozzles, as per ASME PTC-6, need special care for high accuracy (especially for feed water flow measurement) as these are used for performance testing of steam turbines in utility plants. As per PTC requirements the beta ratio is limited within 0.25−0.5 with inlet/outlet sections of 20 and 10D, respectively. Also, there is requirement for a flow straightener as per ASME code (the standard may be referred to). In the condensate section, normally a flanged flow nozzle assembly is used. However, for high-pressure applications, a welded assembly with plugged inspection port is used. With flow nozzles, as per ASME PTC 6, an accuracy of 0.1%−0.3% FSD is possible. Fig. II/3.1.0-3 (RHS) also shows a throat tap for a Venturi flow nozzle.

3.2.2 TAPPING DIAMETER AND SOURCE POINT

Tapping diameter source point details, as discussed in Subsection 2.2.2, could be adapted here based on applicability. Fig. II/2.2.2-1 is also applicable here.

1. **Tapping diameter:** Some guidelines for tapping diameters are available in ISO 5167-3:2003 (refer to articles 5.1.5.1 and 5.2.5.2.). For radius tapping the diameter should be less than 0.13D and 13 mm. In the case of a corner tap, the width of the annular slot (a) or single tapping diameter (δ) is related to the beta ratio as per details below:

   For $\beta \le 0.65$ $0.005 \le a$ or $\delta \le 0.03D$.
   For $\beta > 0.65$ $0.01 \le a$ or $\delta \le 0.02D$.
   For any value of β; clean fluid, 1 mm ≤ a, δ ≤ 10 mm; vapor, 1 mm ≤ a ≤ 10 mm; and for vapor and liquefied gas, 4 mm ≤ δ ≤ 10 mm.

   In the case of D-D/2 and flange tapping diameter consideration is not critical. More guidance is found in "API MPMS 14.3.2 (API 2000)—the tapping diameters must be 9.5 mm (3/8″) for 2 and 3″ pipes and 12.7 mm (1/2″) for 4″ pipes and larger".
2. **Pressure tapping source connection:** Refer to Subsection 2.2.2.2 above (as applicable) for connection details. Apart from the type of source point and connections shown in Fig. II/2.2.2-1, other types of tappings with welded adapters as shown in shown in Fig. II/3.2.2-1 are often used.

FIGURE II/3.2.2-1 Welded adapter tapping. *This figure has been developed based on a figure from Technical Information; Intra Nozzle; Flow Nozzle; Intra Automation, February 2011. http://www.saato.fi/datafiles/userfiles/File/Intra-mittasuutin%20IFN.pdf.*

3.2.3 FLOW NOZZLE MOUNTING

From the mounting point of view there are five kinds of flow nozzle arrangements. Some are applicable to only one kind of design. These flow nozzle arrangements are:

- Flange-mounted flow nozzle;
- Weld in flow nozzle;
- Carrier-mounted flow nozzle;
- Holding ring type flow nozzle;
- Knock pin type flow nozzle.

Carrier ring details have been explained already in connection with the orifice plate in the above section; hence it needs no further explanation.

1. **Flange-mounted flow nozzle:** Flange-mounted flow nozzles with D-D/2 tapping and throat tapping are depicted in Fig. II/3.2.0-1A and C, respectively. In this arrangement the flow nozzle is inserted between pipe flanges. Here, as stated above, the tappings could be radius tapping and/or throat tapping. In Fig. II/3.2.0-1 detailed arrangements for throat tapping as per ASME PTC 6 have also been given.
2. **Weld in flow nozzle arrangement:** a weld in flow nozzle mounting is depicted in Figs. II/3.2.0-1B and II/3.2.0-2. Radius tappings for the flow nozzle have also been shown therein. Weld in flow nozzles are used mainly in high-temperature and high-pressure applications. In this arrangement the flow nozzle is welded between two pipe pieces. In many boiler applications a spool piece form piping vendor is sent to the flow nozzle manufacturer so that the flow nozzles can be fitted to it and supplied as a complete arrangement. There are regulations regarding welding for high-pressure applications in boilers. Each country may have different regulations to avoid boiler explosions, etc., e.g., the Indian Boiler Regulations (IBR). Other countries may have different standards, e.g., the National Board of Boilers and Pressure Vessel inspector, who is responsible for construction and stamping as per various standards such as ASME/API, ANSI to name a few only. Under this, it is necessary to get the design approved by the relevant authority. For that reason, detailing of welding, edge preparations, etc. are given in Fig. II/3.2.0-2. (This is a typical arrangement for IBR.)
3. **Carrier-mounted flow nozzle:** This is similar to the carrier arrangement of the orifice plate discussed in Subsection 2.3.3.2 and is also used for flow nozzle arrangement carrier rings

as shown in Fig. II/3.1.0-3 for an ISA 1932 flow nozzle. Normally these have corner tapping as already discussed. The carrier ring has already been discussed in connection with the orifice plate.

4. **Holding ring type:** The holding ring type flow nozzle has been shown in the LHS part of Fig. II/3.2.3-1. In this arrangement, as shown in the figure, there is a ring around the flow nozzle to hold the nozzle in position. In this arrangement the ring, pins, and pipe are made of compatible materials. The ring and pin are welded with the pipe, therefore, this design eliminates the welding of dissimilar materials. In this mounting, a radius of, e.g., D-D/2 tapping is used.
5. **Knock pin arrangement:** The arrangement is very similar to the one discussed above, only in this case instead of a ring, two pins knock out the pipe, i.e., pins are fitted with the nozzle which is welded at the pipe sections by a boring arrangement as shown in Fig. II/3.2.3-1 (RHS). This is rather difficult to manufacture and so is not popular. Here, for the same reason as discussed in Subsection 3.2.3.4, this arrangement avoids the welding of two dissimilar metals.

3.2.4 IMPULSE LINE INSTALLATION

In this section short discussions have been provided for impulse line installation, which is part and parcel of flow metering, especially for head type flow measurement. Figs. II/3.2.4-1 and II/3.2.4-2 show the impulse *line* installations for two probable cases, namely transmitter below and above the source point, respectively. Depending on the usage, discussions put forward in Section 2.2.4 with associated subsections are applicable here and are therefore not repeated. Also, Figs. II/3.2.4-1 and II/3.2.4-2 are self-explanatory, so these are not described again. Here, one important issue is that for a flow element in a vertical pipe. In a vertical pipe, the impulse line from the upper and lower points should be brought to the same level before these are taken to the transmitter, which could be located either above or below the flow element. In the case of steam/gas installations, the impulse line from the upper tapping point should be taken to the transmitter. Similarly, for liquid services, the lower tapping impulse line should be brought to the level of the upper tapping point. Both the impulse lines should be kept as close as possible so that there should not be any chances of temperature

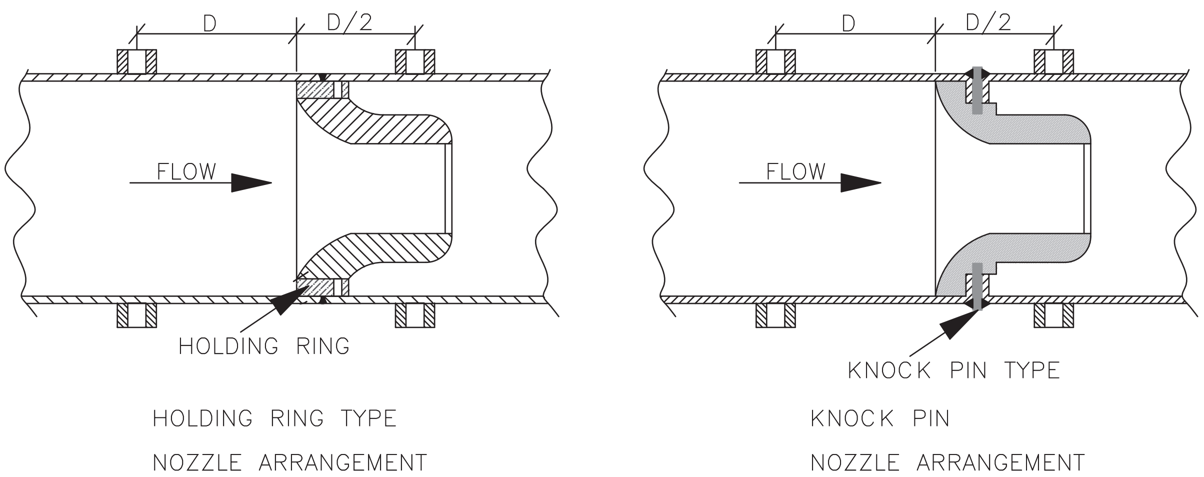
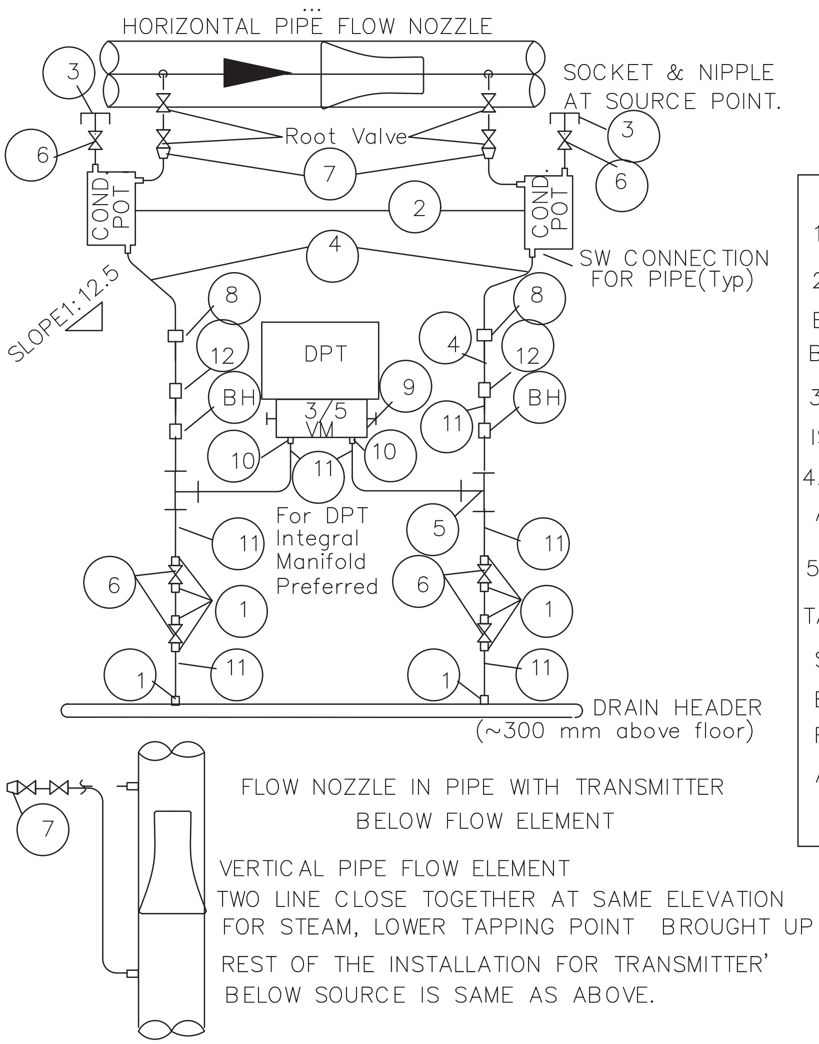


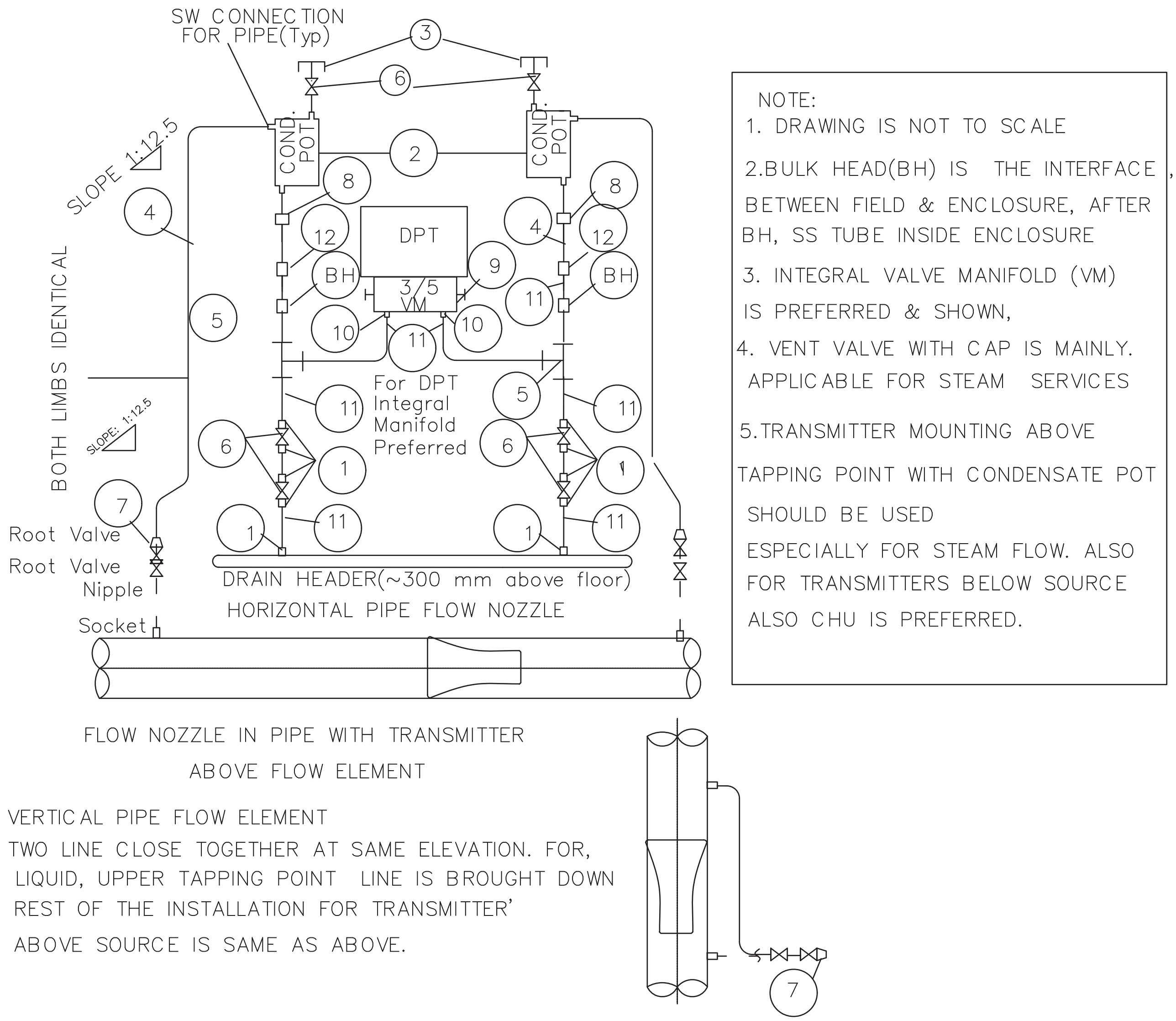
FIGURE II/3.2.3-1 Holding ring and knock pin arrangements for nozzle.



NOTE:
1. DRAWING IS NOT TO SCALE
2.BULK HEAD(BH) IS THE INTERFACE, BETWEEN FIELD & ENCLOSURE, AFTER BH, SS TUBE INSIDE ENCLOSURE
3. INTEGRAL VALVE MANIFOLD (VM) IS PREFERRED & SHOWN,
4. VENT VALVE WITH CAP IS MAINLY. APPLICABLE FOR STEAM SERVICES
5.TRANSMITTER MOUNTING ABOVE TAPPING POINT WITH CONDENSATE POT SHOULD BE USED ESPECIALLY FOR STEAM FLOW. ALSO FOR TRANSMITTERS BELOW SOURCE ALSO CHU IS PREFERRED.

BILL OF MATERIALS	
ITEM NO.	ITEM DESCRIPTION
1	SOCKET WELD TUBE CONNECTOR OF SUITABLE SIZE TO MATCH TUBE SIZES. & CONNECTORS.
2	3 PORT COND. POT WITH SW CONNECTION for PIPE
3	3/4"/ (1/2)" NPT(F) AS/CS CAP
4	3/4 / (1/2) " IMPULSE PIPE SCH: 40/80/160..
5	1/2"/3/4" EQUAL TEE for Tube (IN ENCLOSURE) OR: 1/2"/3/4"SW EQ.TEE for Pipe(FIELD)
6	3/4"/ (1/2)" Socket Weld GLOBE VALVE
7	3/4" X 1/2" SW REDUCER
8	1/2" / 3/4" PIPE UNION
9	3/5 FORGED VALVE MANIFOLD MATERIAL TO SUIT APPLICATION
10	SUITABLE ADAPTER FOR Valve Manifold for tube Connection e.g.Male Connector of suiatble Rating
11	1/2"/3/4" SS TUBE
12	1/2" / 3/4" PIPE X TUBE UNION

FIGURE II/3.2.4-1 Impulse line for flow nozzle, 1. *DPT*, differential pressure transmitter; *VM*, valve manifold.



BILL OF MATERIALS

ITEM NO.	ITEM DESCRIPTION
1	SOCKET WELD TUBE CONNECTOR OF SUITABLE SIZE TO MATCH TUBE SIZES. & CONNECTORS.
	3 PORT COND. POT WITH SW CONNECTION for PIPE
2	3/4"/ (1/2)" NPT(F) AS/CS CAP
3	3/4 / (1/2) " IMPULSE PIPE SCH: 40/80/160..
4	1/2"/3/4" EQUAL TEE for Tube (IN ENCLOSURE) OR: 1/2"/3/4"SW EQ.TEE for Pipe(FIELD)
5	3/4"/ (1/2)" Socket Weld GLOBE VALVE
6	3/4" X 1/2" SW REDUCER
7	1/2" / 3/4" PIPE UNION
8	3/5 FORGED VALVE MANIFOLD
9	MATERIAL TO SUIT APPLICATION
10	SUITABLE ADAPTER FOR Valve Manifold for tube Connection e.g.Male Connector of suiatble Rating
11	1/2"/3/4" SS TUBE
12	1/2" / 3/4" PIPE X TUBE UNION

FIGURE II/3.2.4-2 Impulse line for flow nozzle, 2. *DPT*, differential pressure transmitter; *VM*, valve manifold.

difference between the two limbs. The discussions presented here are not only applicable to flow nozzles but also applicable to other flow elements also.

3.2.5 STRAIGHT LENGTH REQUIREMENTS

Like other head type flow elements, for flow nozzles there is also a requirement for straight pipe length to obtain greater accuracy. Basically, these straight length requirements do not vary much between the orifice plate and flow nozzle, and are a good approximation. However, there are separate charts available in ISO 5167 parts 2 and 3 for orifice plates and nozzles, respectively. Table 3 of ISO 5167-3:2003 lists the upstream and downstream straight length requirements. In connection with the orifice plate, some of these requirements based on the ASME standard have already been presented. In Table II/3.2.5-1 a summary of the required straight length for nozzles and Venturi nozzles is presented. This is a summary only.

TABLE II/3.2.5-1 Summary of Straight Length Requirements (ISO 5167-3:2003)

Fittings (Row)/Beta Ratio (Col)		0.2	0.4	0.6	0.7	0.8
Upstream length[a]	Single 90 degrees bend or Tee	10	14	18	28	46
	Two or more 90 degrees bend in different planes	34	36	48	62	80
	Full open gate valve (for globe valve length is ~1.5 times)	12	12	14	20	30
	Thermometer pocket (0.03−0.13D)	20	20	20	20	20
	Abrupt symmetrical reduction	30	30	30	30	30
Downstream[a]	For above fittings	4	6	7	7	8

[a] *Straight lengths are in multiples of inside pipe diameter D.*

3.2.6 PERMANENT PRESSURE LOSS

From a permanent pressure loss (PPL) point of view, a flow nozzle is better than an orifice plate, but less so than other flow elements, such as Venturi tubes, etc. Typical permanent pressure losses for these flow elements are depicted in Fig. II/3.2.6-1. From the curve it can be seen that the orifice is responsible for maximum pressure loss but the same DP flow nozzle has a lower drop in pressure. The V-cone is also nearby. However, the Venturi discussed in the next section has the lowest pressure drop/permanent loss.

3.3.0 Discussions on ISO 5167-3:2003 Standard

As per the standard, the basic principle of measurement is based on a flow nozzle in a pipe in which fluid is *running full.* The standard put forward the discussions clearly in three parts. Article 5.1 of the standard deals with an ISA nozzle, while articles 5.2 and 5.3 deal with long radius (ASME) nozzles and Venturi nozzles, respectively.

3.3.1 ISA NOZZLE: ISO 5167-3:2003

1. **Nozzle profile:** The basic profile of an ISA flow nozzle as depicted in Fig. II/3.1.0-3 has:
    - Flat inlet surface "A" perpendicular to the pipe center line;
    - Two converging surfaces "B" & "C." B is tangential to flat surface A at $d < 2/3D$. The circumference C is tangential to the arc B and throat E;
    - Cylindrical throat E;
    - Sharp edge G and to protect the same, is the recessed part F;
    - Thickness (represented in standard as H) should be $<0.1D$.

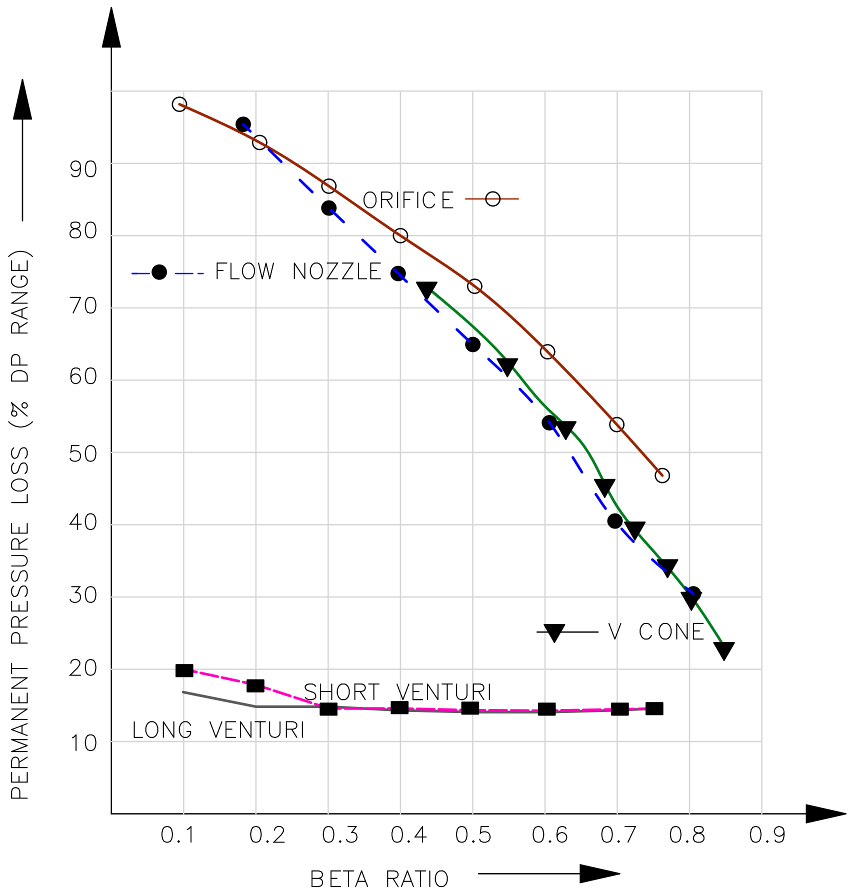


FIGURE II/3.2.6-1 Permanent pressure loss for flow elements.

2. **Limit of use:** The nozzle should follow the guidelines presented below:
   - 50 mm $\leq D \leq$ 500 mm;
   - $0.3 \leq \beta \leq 0.8$ and R_{eD} as per guideline below;
   - R_{eD} in the approximate range of 10^4 to 10^7 (with some nonoverlapping range with variation of beta ratio).
3. **Discharge coefficient:** C_d as seen in connection with the orifice is a function of β and R_{eD}. This can be calculated as follows:

$$C_d = 0.99 - 0.2262\beta^{4.1} - \left(0.00175\beta^2 - 0.0033\beta^{4.15}\right)\left(10^6/R_{eD}\right)^{1.15} \quad \text{(II/3.3.1.3-1)}$$

Values of C_d against β and R_{eD} are presented in the standard in Table A.1.

4. **Expansibility factor:** For β, R_{eD} D specified in Subsection 3.3.1.2, expansibility ε is given by:

$$\varepsilon = \left\{\left(\kappa\tau^{2/\kappa}/\kappa - 1\right)\left(1 - \beta^4/1 - \beta^4\cdot\tau^{2/\kappa}\right)\left(1 - \tau^{(\kappa-1/\kappa)}/1 - \tau\right)\right\}^{1/2} \quad \text{(II/3.3.1.4-1)}$$

where κ is the isentropic exponent and τ stands for pressure ratio.

5. **Uncertainty:** The standard also gives the uncertainty of various parameters;
   - *Discharge coefficient C_d:* 0.8% for $\beta \leq 0.6$; $(2\beta - 0.4)$% for $\beta \geq 0.6$
   - *Expansibility factor ε:* 2 $(\Delta p/P_1)$%

3.3.2 LONG RADIUS NOZZLE: ISO 5167-3:2003

1. **Profile:** Convergent quarter ellipse section as shown in Fig. II/3.1.0-2 for various beta ratios detailed in Table II/3.0.0-1. Initially there is a convergent section (quarter of an ellipse) and after that there is a cylindrical throat with diameter d and plain end as shown in Fig. II/3.1.0-2.
2. **Limit of use:** The nozzle should follow the guidelines presented below:
   - $50\ \text{mm} \le D \le 630\ \text{mm}$;
   - $0.3 \le \beta \le 0.8$ and R_{eD} as per guideline below;
   - R_{eD} in the approximate range of 10^4 to 10^7.
3. **Discharge coefficient:** C_d as seen in connection with the orifice is a function of β and R_{eD}. This can be calculated as follows:
   - $$C_d = 0.9965 - 0.00653\left(10^6\beta/R_{eD}\right)^{0.5} \quad \text{(II/3.3.2.3-1)}$$
   - Values of C_d against β and R_{eD} are presented in the standard in Table A.2.
4. **Expansibility factor:** same as an ISA nozzle if within the limit of use mentioned above.
5. **Uncertainty:** The standard also gives the uncertainty of various parameters:
   - *Discharge coefficient C_d:* 2% for beta between 0.2 and 0.8
   - *Expansibility factor ε:* 2 $(\Delta p/P_1)$%

3.3.3 VENTURI NOZZLE: ISO 5167–3:2003

1. **Profile:** As shown in Fig. II/3.1.0-3 in the upstream side it is identical to an ISA nozzle. It consists of a convergent section, rounded profile, cylindrical throat, and divergent outlet section.
2. **Limit of use:** The nozzle should follow the guidelines presented below:
   - $65\ \text{mm} \le D \le 630\ \text{mm}$; $d \ge 50\ \text{mm}$;
   - $0.316 \le \beta \le 0.775$ and R_{eD} as per guideline below;
   - R_{eD} in the approximate range of $(0.15–2)\ 10^6$.
3. **Discharge coefficient:** C_d as seen in connection with orifice is a function of β and R_{eD}. This can be calculated as follows:
   - $$C_d = 0.9858 - 0.196\,\beta^{4.5} \quad \text{(II/3.3.3.3-1)}$$
   - Values of C_d against β and R_{eD} are presented in the standard in Table A.2.
4. **Expansibility factor:** same as an ISA nozzle if within the limit of use mentioned above.
5. **Uncertainty:** The standard also gives the uncertainty of various parameters:
   - *Discharge coefficient C_d:* $(1.2 + 1.5\beta^4)$%
   - *Expansibility factor ε:* $(4 + 100\ \beta^8)$%

3.4.0 Calibration

As stated in connection with the orifice plate engineering calculation, dimensional details are a major issue in ensuring higher accuracy. Manufacturing is another issue where the elements must be manufactured within tolerance. Inspection also takes place prior to acceptance to ensure accurate manufacturing. However, in some specialized cases flow nozzles are calibrated with the help of various methods as discussed earlier. In such cases, the help of specialized agencies is often sought. In all such cases calibrations are done and traceability is maintained. As per ASME PTC6 there may be requirements for flow calibration at each section. Such calibrations are undertaken only at recognized facilities. These calibrations are done under conditions similar to those in the actual installation. The selection of the calibration facility and analysis of the calibration data are important to ensure and establish the slope of the calibration curve. Apart from piping arrangements, Reynolds number, water temperature, and other flow conditions are used as close to actual conditions as possible. The calibration should be carried out for at least 20 acceptable points over a wide range of Reynolds numbers. The code recommends that the value of the coefficient be established at the highest Reynolds number possible so that this effect is minimal [11].

3.5.0 Specification/Data Sheet

The importance of units in flow metering cannot be overestimated. As stated in Section 2.5.0, the unit of specification is very important for calculations. All units should be specified as per the standard to be used. If necessary, one may have to convert the unit as per the standard to be used. In the following table SI/CGS units are given. The specification of flow nozzles has been specified in Table II/3.5.0-1. The data sheet provided here is generalized in nature, generally applicable to ASME/ISA/Venturi nozzles. For any specific case, nonapplicable parts may be deleted, and any additional special features may be indicated in point 25 in the table. While specifying the data, the limit of use of the applicable standard should

TABLE II/3.5.0-1 Specification for Flow Nozzle (Generalized)

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Type	(a) ISA 9132/ASME Type hi beta/ ASME Type low (b) ISA Nozzle (c)Venturi nozzle		User to choose.
2	Process fluid	To specify the exact medium and liquid/gas/steam		
3	Flow data	Max/Min/Nor.		Nor: Normal
4	Other physical parameters	**(a)** Upstream Abs. Pressure Abs. Max/min/Nor **(b)** Downstream Abs. Pressure Abs. Max/min/OP **(c)** Temperature Max/min/Nor **(d)** Density: **(e)** Viscosity @ temperature **(f)** Reynolds number: for turbulent flow **(g)** Gas molar weight **(h)** Specific heat ratio **(i)** Expansion factor		**1.** To specify OP = operating Max Pr./is dictated by flange rating (pipe schedule) and Max. temp. is guided by material selection and application **2.** Data as applicable to be specified
5	Pipe dimension and materials	Pipe NB and schedule		Pipe schedule is necessary for flange rating
		Pipe internal diameter		
		Machined bore (*later by manufacturer*)		
		Pipe material: Carbon steel, alloy steel, stainless steel with ASTM code		
6	Tapping style	Corner/throat/radius	To select	
7	Pairs of tappings	1/2/3		To specify qty.
8	Numbers of tappings and fittings to be supplied	Quantity in pair (specify)	To specify	

Continued

TABLE II/3.5.0-1 Specification for Flow Nozzle (Generalized)—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
9	Tapping connection	Normally ½″ NPT/BSPT and others like ½″ socket weld-/welded adapter/Flange connections are also available	User to specify based on source connection type selected	
10	Mounting style	Between flange/weld in/butt welded/on holding ring/knock pin	To specify with details	
11	End connection	SORF flange/weld in/butt weld		
12	Design standard	ISO5167/BS1042/DIN/ASME MFC-3M/PTC6,PTC19.5/		User to select and specify
13	Calculation standard	ISO5167/BS 1042/ASME MFC 3M, L.K.Spink, AGA-3 others.		
14	Carrier ring	For ISA nozzle, specify if corner tap/slot		As applicable, to specify
15	Flange size/pressure rating/standard	Nominal size, and pressure rating (*150/300/600 lb class*) (normally matching with pipe schedule)/type such as slip on/weld neck, threaded, socket welded with RF or RTJ, etc. standards: *ASME/ANSI B16.96, BS, JIS, DIN, …*		
16	Flow nozzle material	Commonly available materials: SUS304304L, SUS316/316L, SST316Ti DIN 1.4571, Hastelloy C-276 ASTM B575, Monel 400, Aluminum, etc., others.		To choose based on application
17	Carrier ring (ISA)	SS400, SF440A, SUS304, SUS316		As above
18	Flange material	ASTM-A105N; ASTM-A350 LF2 ASTM-A182 F5, F9, F11 and F12; stainless steel ASTM-A182 F316(L), F304(L)		Select based on application/standard. (For other standard equivalent materials)
19	Gasket size/ material	1.6 or 4.5 (spiral wound)/Material: CAF (IS: 2712 Gr 0/1)/SS spiral wound (+CAF or Grafoil or, PTFE)/ 6500AC nonasbestos/Teflon, graphite compound GF300/pure graphite		Material selection dependent on pressure and temperature rating
20	Nuts/bolts Material	ASTM-A194 GR 2H and H8/ASTM −A193 B7 L7		Typically used material
21	Accessories	Sockets, nipple, root valve, condensate pot		For each qty, material, size, etc. as applicable

Continued

TABLE II/3.5.0-1 Specification for Flow Nozzle (Generalized)—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
22	Assembly length	To be specified by manufacturer later		
23	Testing	Hydro-testing, Radiography Additional options: Magnetic particles, PMI, gas and water calibrations		As desired to specified. Also to specify required test certificate as applicable
24	Calculated/final data	(a) Differential range (b) Inlet/outlet velocity (c) Upstream/downstream length provided (d) Discharge coefficient/uncertainty (e) Permanent pressure loss		In final data sheet by manufacturer
25	Special feature	If any additional/special feature desired to be specified		

be considered. The limit of use from ISO 5167:2003 has already discussed in this section.

3.6.0 Sonic Nozzle

3.6.1 SONIC FLOW PRINCIPLES

From Section 7.0.0 in Chapter I, we have a basic idea about sonic nozzles. As shown there, it is important for gas flow meter calibrations also. It is worthwhile recalling the discussions in Section 7.3.0 of Chapter I. As shown in Fig. II/3.6.0-1, a sonic nozzle can be conceived of as an inlet converging section with a throat between, where the area is minimum and is followed by a divergent outlet section.

With reference to the above Fig. II/3.6.0-1 let box A at high gas pressure (high capacity to keep the pressure constant in spite of variation in gas velocity) supply gas to flow through the nozzle to exhaust in box B. As stated in Section 7.3.0 of Chapter I, let the box controlling the pressure cause flow through the nozzle. If the back pressure P_B is lowered (or evacuated) to a set value, suddenly the flow through the nozzle stops. This happens when the speed of the gas reaches Mach1, i.e., the velocity of sound is reached. In the opposite side, if PB is further lowered, shock waves will develop. Now, if P_1 is different, P_B will be different to get choked condition. Now, further flow can be established by increasing inlet pressure, P_1. So inlet pressure is the influencing factor for mass flow through the nozzle. Similarly, temperature can influence this choked flow condition. Let the pressure and temperature at which gas stops at the entrane to the nozzle be represented by P_0 and T_0. Now we shall try to develop an equation for mass flow.

From the discussions in Section 7.3.0 of Chapter I and as discussed above it is clear the principle rests on the fact that the gas which passes through the nozzle accelerates up to critical speed, which is equal to the speed of sound, at the throat. Also it has been noted that, under critical flow, the mass flow across the nozzle depends only on the upstream conditions. By utilizing the continuity equation and isentropic equations discussed in Chapter I, the mass flow q_m through the nozzle using the following formula:

$$q_m = A \cdot f(\kappa) \cdot \frac{P_0}{\sqrt{(R/M)T_0}} \qquad \text{(II/3.6.0-1)}$$

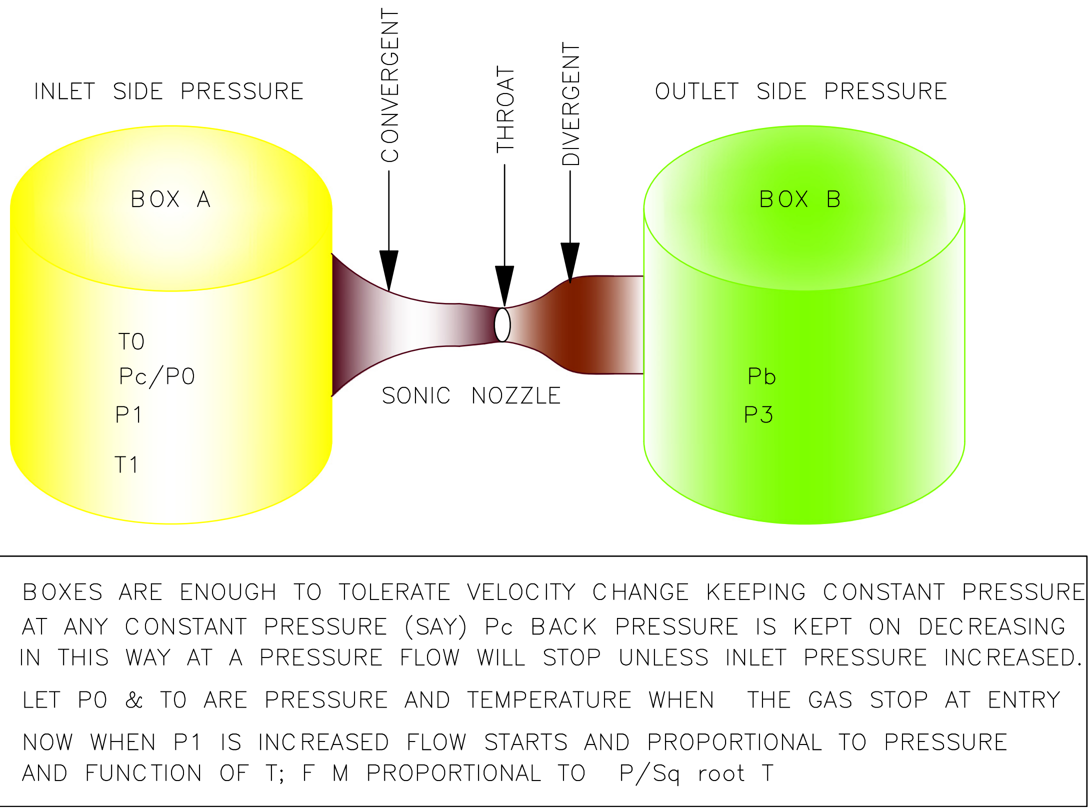


FIGURE II/3.6.0-1 Sonic nozzle principles.

When

$$f(\kappa) = \kappa^{1/2}(2/\kappa + 1)^{(K+1)/2(\kappa-1)} \quad \text{(II/3.6.0-2)}$$

Here, A = area of throat; R = universal gas constant in J/mol K; M = molar mass kg/mol; and κ = isentropic coefficient C_p/C_v.

For actual flow measurement in all gas conditions, such as ideal gas, isentropic flow and pressure of the gas stop upstream of the nozzle, etc., it is necessary to take the help of the discharge coefficient C_d and critical flow C. Here the critical flow C intervening in this relationship depends on the pressure P_0 and the temperature T_0 of the gas stop upstream of the nozzle. So, mass flow will become

$$Q_m = A \cdot C_d \cdot C \cdot \frac{P_0}{\sqrt{(R/M)T_0}} \quad \text{(II/3.6.0-3)}$$

Thus the relationship given in Eq. I/7.3.0-1 is established.

A specification sheet for a sonic nozzle is given in Table II/3.6.0-1.

TABLE II/3.6.0-1 Sonic Nozzle Specification

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Flow range (typical)	10–20,000 nL/min or higher		
2	Gases	Air, nitrogen, SF6, etc. a number of gases, mainly nonhazardous gases. Manufacturer to consult		
3	Accuracy	±0.25% AR or better		
4	Repeatability	±0.10.25% AR or better		

Continued

TABLE II/3.6.0-1 Sonic Nozzle Specification—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
5	Pressure range	10 bar		
6	Temperature range	<100°C		
7	Materials of construction	SS or suitable material		
8	Calibrating gas	Dry air		

With this, discussion on flow nozzles concluded, we look at another flow element, the Venturi tube, which offers much less PPL.

4.0.0 VENTURI TUBE

Italian physicist Giovanni Battista Venturi, in the 18th century, first observed that when fluid passes through a narrow throat, in the middle the fluid speeds up and pressure drops. This was the first basis for a flow element, and the flow element is named after him. Later, in 1887, Clemens Herschel designed a classical Venturi. The main positive issue related to the venture is its low permanent pressure loss and comparatively higher accuracy of coefficient of discharge. These come from the flow element geometry and precision manufacturing available in the modern era. The coefficient of discharge of a Venturi tube is almost constant and seldom varies more than a fraction of 1% [1]. Venturi tubes are normally used for noncorrosive clean fluids. However, often they are deployed for air flow measurements with dirt (e.g., primary air flow in boiler applications). In such cases necessary precautions (such as use of a drain pot) need to be taken. For slurry and/or for two-phase fluid flow (i.e., solids in liquid) applications, eccentric Venturi are also used. In the case of liquid applications, Venturi should always be *full*. Broadly, Venturi can be classified into three categories. These are:

- Classical/long Venturi;
- Short Venturi;
- Eccentric Venturi.

Again, based on manufacturing techniques, Venturi can be classified as:

- Cast Venturi;
- Fabricated Venturi;
- Machined Venturi.

It is better to look at the Venturi geometry to see how it helps to have less PPL. General discussions on construction and profile details are covered in Section 4.1.0.

4.1.0 Construction Details and Features of Venturi Tubes

1. **Classical Venturi tube:** The classical Herschel Venturi has a very long flow element, characterized by a tapered inlet and a diverging outlet. Fig. II/4.1.0-1 shows the profile and geometry of a classical Venturi. A classical Venturi mainly consists of the following sections moving along the direction of flow.
   - *Cylindrical section:* The cylindrical inlet section matches the pipe section diameter. At this section the static upstream pressure head is measured.
   - *Converging conical section:* The converging conical section, the cross-sectional area decreases along the direction of flow so as to cause an increase in fluid velocity. As a consequence of the increase in fluid velocity there will be a decrease in the pressure head of the fluid. In this section the angle with which convergence occurs

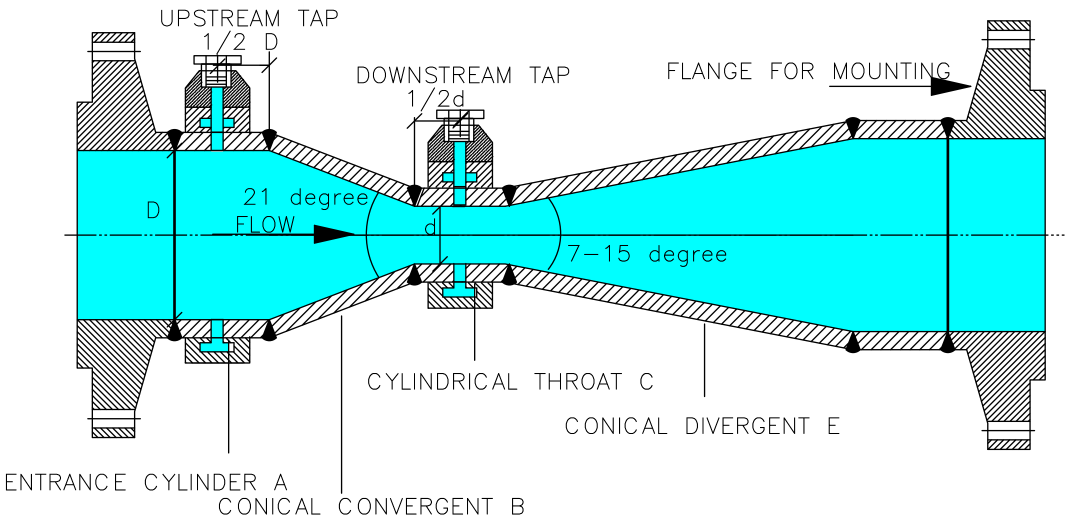


FIGURE II/4.1.0-1 Classical Venturi tube profile and flange mounting.

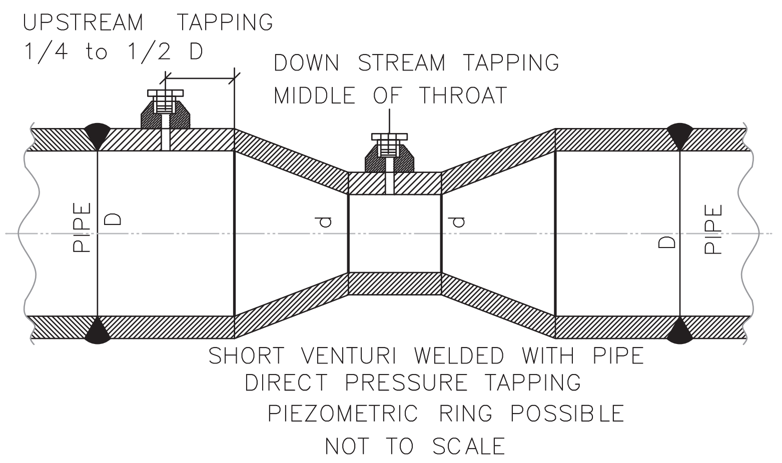
is ∼21 degrees, i.e., more than that in the diverging outlet section.

- *Cylindrical throat:* The converging conical section discussed above is followed by a cylindrical throat section. Since there is no change in cross-section, the velocity is constant, so that the decreased pressure head can be measured.
- *Diverging conical section:* Finally, there is a diverging pressure recovery cone. Here the velocity decreases and almost all of the original pressure head is recovered. The angle with which there is divergence in the outlet section is between 7 and 15 degrees.

A cast iron body with a stainless steel throat section is quite common in classical Venturi. However, they can be manufactured with other materials also. Upstream and downstream tapping points are taken from the cylindrical sections as shown in Fig. II/4.1.0-1. Upstream and downstream tappings are located based on the pipe internal diameter ***D*** and throat diameter ***d***, respectively. Upstream tapping is located ½D away (toward upstream side) from the joining point of the cylindrical section with the convergent section. Downstream tapping is as ½ d form (toward downstream side) the joining point of convergent section with throat. As per ISO 5167 the length of the throat is d, so effectively this is at the middle of the throat. Usually a piezometric ring or an annular chamber with six to eight pressure taps is created to get the average pressure. There could be 2–4 pairs of pressure taps from the external face to the annular chamber. The beta ratio is normally between 0.3 and 0.75. The flow coefficient for the classic Venturi is 0.984, with an uncertainty tolerance of ±0.75%. The slowly changing divergence (shallower angle) in the outlet section over a length greater than the inlet section reduces the overall permanent pressure loss by smoothly decelerating the flow-arresting turbulence.

2. **Short form of Venturi:** The cost of a Venturi is quite high and as the length of the Venturi increases the cost increases sharply. The reason behind opting for a short form of Venturi was mainly commercial. It also has a shorter laying length. Short Venturi came into the market in 1950 [1]. A short form Venturi is shown in Fig. II/4.1.0-2A. There are two issues which are implemented in the shorter form of Venturi. Since the length is shorter, there is a major impact on the divergent outlet whose recovery divergent angle is increased from 7–15 to 21 degrees. In short Venturi single pressure taps are used.

(A)



(B)

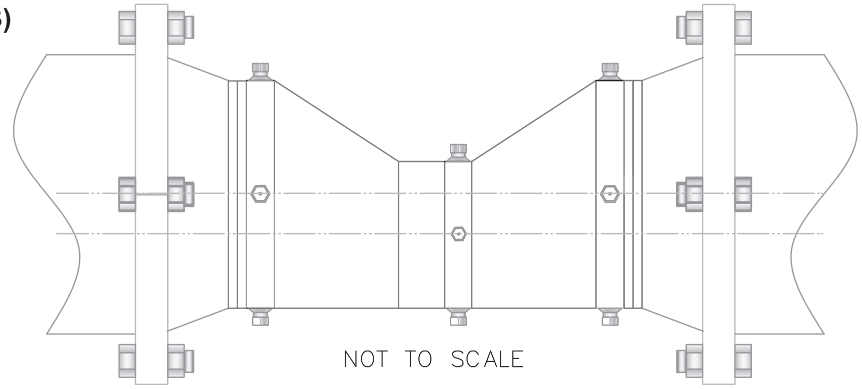


FIGURE II/4.1.0-2 Short form and eccentric Venturi. (A) Short Venturi (weld mounting). (B) Eccentric Venturi tube.

However, piezometer connections are used for very large tubes and/or for accurate average pressure. Upstream pressure tapping is located based on pipe internal diameter ***D***. Pressure tappings are located as shown in Fig. II/4.1.0-2A. Upstream tapping is located between ¼D to ½D (toward the upstream side) from the joining point of the cylindrical section with the convergent section. Downstream tapping is at the middle of the throat with diameter ***d***. These are welded from a variety of materials depending on usage. The beta ratio is between 0.3 and 0.75. The discharge coefficient is around 0.98 and an accuracy of ±1.5% is achievable. On account of the absence of any sharp edges/corners or sharp changes in contour, etc., it is often used in slurry and dirty fluid applications that tend to build up or clog other primary devices. For dirty fluid measurements, inserted sealed sensors that are mounted flush with the pipe and throat inside wall should be used.

3. **Eccentric Venturi:** An eccentric Venturi is shown in Fig. II/4.1.0-2B. Eccentric venturimeters have a good number of applications in the measurement of sand-oil, dirty fluid flow, and two-phase (solid liquid) flow. When two-phase/solid liquid or dirty fluids flow in a horizontal pipe, there is excessive wear/erosion at the bottom of the pipe. This is due to high-velocity solid particles. Naturally, in Venturi when there is acceleration of fluid at the throat, there will be more wear at the bottom. This changes the discharge coefficient C_d. Therefore C_d becomes unpredictable. Also, as coarse solid particles tend to settle

at the bottom, the performance of normal Venturi will deteriorate [12]. In the case of an eccentric Venturi, such effects are minimized. An eccentric Venturi is capable of providing improved cladding ability with similar pressure loss and accuracy (when compared with normal Venturi). In eccentric Venturi the H/D ratio is very important to get the desired performance. Here H stands for the throat height from the bottom. Further discussions on eccentric Venturi in slurry applications are also available in Subsection 3.1.1.1 of Chapter VII (slurry flows).

4.1.1 FEATURES OF VENTURI TUBES

For a number of reasons the Venturi is preferred to other head type flow elements. Some of their unique features are listed below.

1. **Advantages:**
   - Venturi can be fabricated as part of the duct and are especially useful in cases where duct sizes are large and where the flange connection is not allowed.
   - It offers a much higher flow rate for the same beta when compared with other head type flow elements, e.g., it offers nearly 60% more flow capacity than an orifice plate.
   - On account of smooth construction it can offer accuracy for a longer period and wider flow range.
   - It has much less damming effect to solid particles and foreign body.
   - It offers very low permanent pressure loss.
   - It is available for quite large pipe sizes.
   - It creates less pressure drop across the restriction.
   - It has less upstream and downstream straight pipe requirements for installations.
2. **Disadvantages:** There are a few disadvantages to Venturi tubes, these are:
   - It is very expensive, and as the size increases cost goes up sharply.
   - It is bulky and requires large installation.
   - Inspection is quite difficult.
   - Its use a lower pipe size and so is not popular.
   - It has limitations in low Reynolds numbers.

4.2.0 Tapping Mounting and Installations

As with the flow nozzle we first discuss the tapping details.

4.2.1 TAPPING DETAILS

1. **Tapping style:** The tapping style for the classical Venturi is slightly different from others. The upstream and downstream tapping point locations are normally expressed in terms of pipe inside diameter ***D*** and throat diameter ***d***, respectively. Distance tolerance or D between 100 and 150 mm $\pm$ 0.25D and is the same for D > 150 is +0/−0.25D
   - *Classical Venturi:* In a classical Venturi, normally, an annular slot or piezometric ring is formed for pressure tappings, of which upstream tapping is normally located at the cylindrical entrance ½D away toward the upstream from the junction point of the cylindrical entrance and convergent Venturi. The downstream pressure tapping point is located at throat ½ d distance away from the junction point of the throat with an convergent inlet. These tapping points are detailed in Fig. II/4.1.0-1.
   - *Short form and eccentric Venturi:* Upstream tapping is located between ¼D to ½D away (toward the upstream side) from the joining point of the cylindrical section with the convergent section. The downstream tapping is at the middle of the throat with diameter ***d***. When the length of the throat is d then the location is the same as that for a classical Venturi.
2. **Tapping diameter and source point:** For a classical Venturi annular chamber/piezometric ring or triple T as mentioned in ISO 5167-1:2003. This piezo ring is created to take the average pressure created by the least pressure tappings which must be flush with the pipe wall (ensured by inspection). From this ring

external tappings are taken as shown in Fig. II/4.1.0-1. Diameters as per ISO 5167-4:2003 are as follows:

- *Tapping diameter for larger d:* For $d \geq 33.3$ tapping diameter between 4 and 10 mm but <0.1D (upstream tapping) and <0.13d for throat tapping.
- *Tapping diameter for smaller d:* For $d < 33.3$ tapping diameter: upstream tapping between 0.1d and 01D and throat tapping: 0.1d−0.13d.
- *Source point:* Source point details as elaborated earlier in Section 2.2.2 and in Fig. II/2.2.2-1 are valid.
- *ISO recommendations:* Pressure tappings shall be as small as compatible with the fluid to be used (ISO 5167-4:2003, page 7).

3. **Pressure tapping connection:** Normally ½″ NPT/BSP threaded tappings are used. Apart from these there could be a socket weld connection as per DIN 2559 or ANSI B16.25. Also, flange connections as in ANSI B16.5/Din are possible.

4.2.2 VENTURI MOUNTING DETAILS

There are three kinds of mountings of Venturi encountered in Venturi flow elements.

1. **Flange mounting:** As shown in Fig. II/4.1.0-1 the Venturi could be placed between the two flanges which could be weld in/SORF type. Standard flanges could be ANSI B16.25 flanges,/DIN or ANSI B16.5 standards.
2. **Welded mounting:** A welded connection for a Venturi mounting is shown in Fig. II/4.1.0-2.

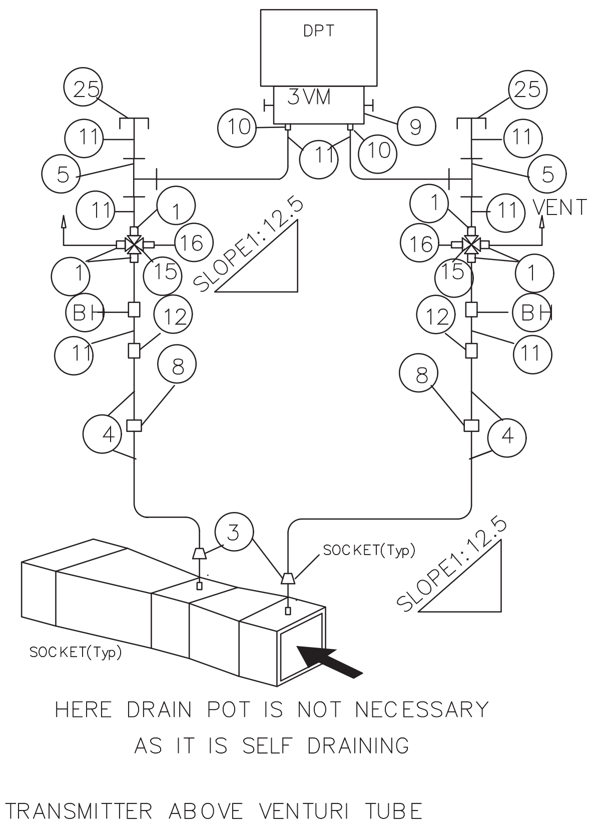
There is another kind of mounting called a clamped mounting.

4.2.3 IMPULSE PIPE INSTALLATION FOR VENTURI

In this section short discussions are provided for impulse line installation, which is part and parcel of flow metering, especially for head type flow measurement. Fig. II/4.2.3-1 and Fig. II/4.2.3-2 show the impulse *line* installations for two probable cases, namely, transmitter below and above the source point, respectively. Depending on usage, discussions put forward in Section 2.2.4 with associated subsections are applicable here; these are not repeated. Here the installations have been presented for gas flow measurement in a duct, but can be applied to liquid flow measurement in a similar manner. On account of large size, such venturi meters are fabricated one as duct with different geometry. They normally have flange type connection with duct with the help of nuts and bolts. Drain pots have been used for dirty gases to drain out excess dust. Similarly, for liquids with solids, suitable measures should be taken.

4.2.4 STRAIGHT LENGTH REQUIREMENTS

Like other head type flow elements, the Venturi also has straight length requirements as detailed below; ISO 5167-4:2003 also specifies the same. As the geometry of the Venturi by itself provides some flow conditioning, the piping requirements of the Venturi are usually much less when compared with an orifice plate, etc. There is no known limitation on piping configuration, or straight length requirements in the downstream side of the Venturi tube; with the exception that any valve should be located *at least* 2D from the outlet of the Venturi. Also, there should not be any protruded part in the upstream side of the Venturi. Although the Venturi can operate between 0.3 and 075 beta ratio, most upstream cases have straight length requirements that are significant in the range of 0.4−0.75. Therefore, straight length requirements are given for various restrictions in this beta ratio range in Fig. II/4.2.4-1. The reader is required to obtain the required straight length for reader's beta ratio from the graph directly.



DRAWING IS NOT TO SCALE

BILL OF MATERIALS

ITEM NO.	ITEM DESCRIPTION
1	SOCKET WELD TUBE CONNECTOR OF SUITABLE SIZE TO MATCH TUBE SIZES. & CONNECTORS.
2	NOT USED
3	M42X2 TO 3/4 or 1/2" SW REDUCER
4	3/4"/1/2"IMPULSE PIPE (Length as per routing) SCH:40/80/160(For Material see CHXII Sec. 2.0)
5	1/2"/3/4"EQ. TEE for Tube (Inside Enclosure) 1/2"/3/4" SW EQ.TEEforPipe(Outside enclosure)
6	3/4"/ (1/2") SW GLOBE VALVE(MAT: cH:2)
7	NOT USED
8	1/2" / 3/4" PIPE UNION
9	3 OR 5 VALVE MANIFOLD OF SUITABLE MATERIAL FORGED (For Material see CH XII Sec. 2.0)
10	SUITABLE ADAPTER FOR Valve Manifold for tube connection e.g.Male Connector
11	1/2" / 3/4" SS TUBE OF SUITABLE THICKNESS
12	1/2" / 3/4" PIPE X TUBE UNION
13	NOT USED
14	NOT USED
15	3/4 / (1/2)" SW 4 WAY VALVE (IF DIRTY GAS)
16	QUICK DISCONNECT FITTING(IF DIRTY GAS)
17	NOT USED
22	NOT USED
23	3/4"/ (1/2)" NPT(F) AS/CS CAP
24	NOT USED
25	3/4" / (1/2)" CAP FOR TUBE

NOTE:

1) AFTER BULK HEAD(BH) INTERFACE BETWEEN FIELD & ENCLOSURE, IMPULSE LINE IS SS TUBE.

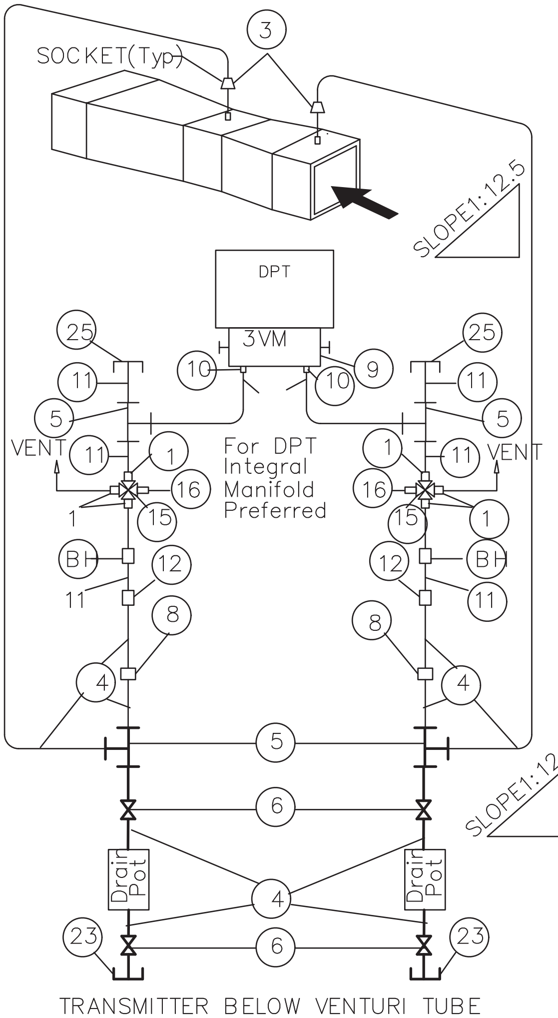
2) SOCKET WELD SOURCE CONNECTION IS PREFERRED TO AVOID CONNECTION MISMATCH.

3) SINGLE ROOT VALVE FOR PRESSURE UPTO 40Kg/cm2

FIGURE II/4.2.3-1 Impulse line installation for Venturi, 1.

4.2.5 PERMANENT PRESSURE LOSS

As stated earlier, the permanent pressure loss (PPL) of a Venturi is on the lower side as compared to other many other types of head type flow elements. In this connection, Fig. II/3.2.6-1 may be referenced. The permanent pressure loss is basically relative pressure loss with respect to the differential pressure range selected for calculation. This depends on a number of factors, such as beta ratio, Reynolds number installation condition, and manufacturing characteristics. In the following discussions, the impact of divergent characteristics, i.e., divergent angle are covered. A long Venturi with an outlet divergence angle between 7 and 15 degrees has a comparatively lower pressure drop than the short form of Venturi. When comparing the PPL of a long Venturi with two extreme outlet angles, it will be found that, in the case of a 15 outlet, there will be a continuous fall in pressure loss from 30% to



DRAWING IS NOT TO SCALE

BILL OF MATERIALS

ITEM NO.	ITEM DESCRIPTION
1	SOCKET WELD TUBE CONNECTOR OF SUITABLE SIZE TO MATCH TUBE SIZES. & CONNECTORS.
2	NOT USED
3	M42X2 TO 3/4 or 1/2" SW REDUCER
4	3/4"/1/2"IMPULSE PIPE (Length as per routing) SCH:40/80/160(For Material see CHXII Sec. 2.0)
5	1/2"/3/4"EQ. TEE for Tube (Inside Enclosure) 1/2"/3/4" SW EQ.TEEforPipe(Outside enclosure)
6	3/4"/ (1/2") SW GLOBE VALVE(MAT: cH:2)
7	NOT USED
8	1/2" / 3/4" PIPE UNION
9	3 OR 5 VALVE MANIFOLD OF SUITABLE MATERIAL FORGED (For Material see CH XII Sec. 2.0)
10	SUITABLE ADAPTER FOR Valve Manifold for tube connection e.g.Male Connector
11	1/2" / 3/4" SS TUBE OF SUITABLE THICKNESS
12	1/2" / 3/4" PIPE X TUBE UNION
13	NOT USED
14	NOT USED
15	3/4 / (1/2)" SW 4 WAY VALVE (IF DIRTY GAS)
16	QUICK DISCONNECT FITTING(IF DIRTY GAS)
17	NOT USED
22	NOT USED
23	3/4"/ (1/2)" NPT(F) AS/CS CAP
24	NOT USED
25	3/4" / (1/2)" CAP FOR TUBE

NOTE:

1) AFTER BULK HEAD(BH) INTERFACE BETWEEN FIELD & ENCLOSURE, IMPULSE LINE IS SS TUBE.

2) SOCKET WELD SOURCE CONNECTION IS PREFERRED TO AVOID CONNECTION MISMATCH.

3) SINGLE ROOT VALVE FOR PRESSURE UPTO 40Kg/cm2

4) IN CASE OF TOO MUCH DUST DRAIN POT IS NECESSARY

FIGURE II/4.2.3-2 Impulse line installation for Venturi, 2.

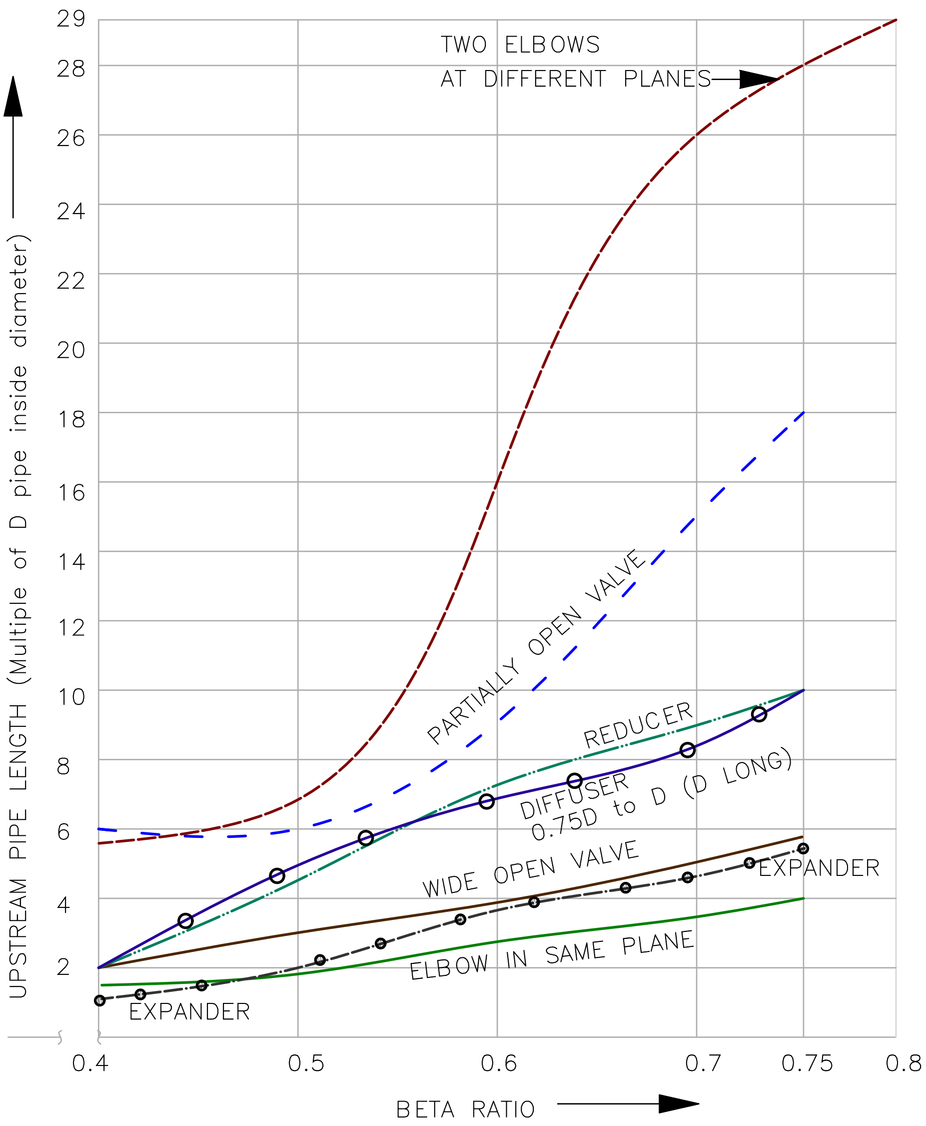


FIGURE II/4.2.4-1 Venturi upstream straight length.

around 10% in the beta ratio range between 0.3 and 0.75. However, in the case of a 7 outlet, the PPL falls from 15% to 10% in the range of beta ratio between 0.3 and 0.5 and is then steady at around 10%.

4.3.0 Discussions on ISO Standard on Venturi (ISO 5167-4:2003)

In this section, short discussions on ISO 5167-4:2003 are presented.

4.3.1 GENERAL DISCUSSION

Under this section light is thrown on the methods of manufacturing and geometrical shapes as per the subject standard.

1. **Types of classical Venturi:** As per the method of manufacturing there are three types of Venturi:
   - *As cast:* As cast convergent—Venturi made by casting in sand mold. Usage: Refer to Table II/4.3.3-1.

TABLE II/4.3.3-1 Discharge Coefficient for Classical Venturi Types

Parameters	As Cast	Machined Conv. Sec	Rough-Welded
Pipe ID range	100–800 mm	50–250 mm	200–1200 mm
Beta range	0.3–0.75	0.4–0.75	0.4–0.7
Reynolds number	$(0.2-2) \times 10^6$	$(0.2-1) \times 10^6$	$(0.2-2) \times 10^6$
C_d for above cond.	0.984	0.995	0.985
Uncertainty of C_d	0.7%	1%	1.5%

Cond., Condition; *Conv.*, Convergent; *Sec*, Section.

- *Machined convergent section:* Convergent section is machined. Usage: Refer to Table II/4.3.3-1.
- *Rough-welded sheet–iron convergent section:* Classical Venturi fabricated by welding. Usage: Refer to Table II/4.3.3-1.

2. **Geometric shape:** The discussions should start with Fig. II/4.1.0-1. In this connection, Subsection 4.1.0.1 may be referenced.
   - *Entrance Section A:* There is entrance cylinder A connecting the convergent section.
   - *Convergent Section B:* The entrance cylinder is connected to the convergent section B with a convergence angle of 21 + 1 degrees.
   - *Throat C:* There is a least-diameter throat with diameter d and length d ±0.03.
   - *Divergent outlet:* Throat C is followed by a divergent section with angle of divergence lying between 7 and 15 degrees and length limited by 2.7 (D−d).

4.3.2 MATERIALS AND MANUFACTURING

Any materials can be used for manufacturing of a Venturi, as long as it can follow the manufacturing process prescribed in the standard. The standard recommends sections B and C be joined as one part, and manufactured from one piece and then machined, but prior to final finishing the two separate parts can be assembled. Centering of E is important and care must be taken to ensure this.

4.3.3 DISCHARGE COEFFICIENT C_D AND UNCERTAINTY OF C_D IN %

The discharge coefficient of classical Venturi types has been listed in Table II/4.3.3-1.

4.3.4 EXPANSION FACTOR ε

For the values of R_{eD}, β, and D given in Table II/4.3.3-1, the expansion factor is given by Eq. II/3.3.1.4-1.

4.4.0 Calibration

Calibration methods of classical Venturi are similar to those described in connection with flow nozzles and orifice plates. General flow calibration methods have been discussed in Section 2.4.0 above. In calibrating facilities, piston provers are normally used for Venturi in natural gas applications, and for liquid flow large and small provers discussed earlier are used.

4.5.0 Specification/Data Sheet for Venturi Tube

The importance of units in flow metering cannot be overestimated. As stated in Section 2.5.0, the unit of specification is very important for calculation. All units should be specified as per the standard to be used and, if necessary, one may

have to convert the unit as per the standard to be used. In the following table SI/CGS units are given. The specification for Venturi has been specified in Table II/4.5.0-1. The data sheet provided here is generalized in nature, and is generally applicable to long classical, short form, and/or eccentric Venturi tubes. For any specific case, nonapplicable parts may be deleted, and any additional special features may be indicated in point 23 in the table. While specifying the data, the limit of use the applicable standard should be considered. The limit of use from ISO 5167:2003 has already been discussed in this section.

A Venturi provides low permanent pressure loss, and because of this it is used in many applications where there is a requirement for low PPL. There are a few proprietary tubes which offer better relative permanent pressure loss, the Dall tube is one of these, and will discussed in the next section.

TABLE II/4.5.0-1 Specification/Data Sheet for Venturi (Generalized)

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Type	(a) Classical long Venturi (b) Short form Venturi (c) Eccentric Venturi		User to choose
2	Process fluid	Same as point 2 of Table II/3.5.0-1		
3	Flow data	Same as point 3 of Table II/3.5.0-1		
4	Other physical parameters	Same as point 4 of Table II/3.5.0-1		
5	Pipe dimension and materials	Same as point 5 of Table II/3.5.0-1		
6	Tapping style	Annular/piezometric/direct; Location upstream ½D (long) ¼ to ½D (short). Downstream middle of throat	To Select	
7	Pairs of tappings	1/2/3		To specify qty.
8	Numbers of tapping-tappings and fittings to be supplied	Same as point 8 of Table II/3.5.0-1		
9	Tapping connection	Same as point 9 of Table II/3.5.0-1		
10	Mounting style	Flange/weld in type/clamp Type, namely, Grayloc	To specify with details	
11	End connection	SORF flange/weld in		If applicable
12	Design standard	ISO5167/BS1042/DIN/ ASME MFC-3M:2004		User to select and specify
13	Calculation standard	ISO5167/BS 1042/ASME MFC 3M, L.K. Spink and others		

Continued

TABLE II/4.5.0-1 Specification/Data Sheet for Venturi (Generalized)—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
14	Flange size/pressure rating/standard	Same as point 15 of Table II/3.5.0-1		
15	Flow element materials	Commonly available materials: SUS304304L, SUS316/316L, SST316Ti DIN 1.4571, Hastelloy C-276 ASTM B575, Monel 400		To choose based on application
		BS1501-151-430A; ASTM A105N/ASTM A106GRB, Aluminum, fiber glass, etc., others		
16	Flange material	Same as point 18 of Table II/3.5.0-1		
17	Gasket size/material	Same as point 19 of Table II/3.5.0-1		
18	Nuts/bolts material	Same as point 20 of Table II/3.5.0-1		
19	Accessories	Same as point 21 of Table II/3.5.0-1		
20	Assembly length	To be specified by manufacturer later		
21	Testing	Hydro-testing, radiography additional and a full range of applicable NDT, documentation and certification		As desired to specified. Also to specify required test certificate as applicable
22	Calculated/final data	(a) Differential range (b) Inlet/outlet velocity (c) Upstream/downstream length provided (d) Discharge coefficient/ uncertainty (e) Permanent pressure loss (f) Accuracy		In final data sheet by manufacturer
23	Special feature	If any additional/special feature desired to be specified		Available: accuracy 0.25%–0.5% FSD, line size from 50 to 1800 mm and pressure. Rating 2500ib class

5.0.0 FLOW TUBE: LO-LOSS FLOW TUBE; DALL TUBE

As stated above, there exist a number of compact proprietary head-type flow elements which are classified as flow tubes. The major advantage of these flow tubes is lower PPL. From the length point of view, short form Venturi tubes are very close. A Dall tube is one such flow tube developed in the UK. Other such flow tubes include the BIF Universal Venturi or the Badger Lo-Loss Flow Tube. All of these tubes vary in contour used, tap locations, and differential pressure and

pressure loss for a given flow and have laying lengths of between 2D to a maximum 4D (D:Pipe ID) [1]. On account of the shorter lay length, flow tubes could be useful in larger sizes. However, these may also require longer upstream pipe runs than the Venturi for proper performance. These longer upstream pipe runs often dilute the real advantage described at the start of this discussion. Another important issue here is discharge coefficient C_d, which is subject to variations with viscosity, Reynolds number. For the effect of these parameters on C_d one needs to rely on the data supplied by the manufacturer. Also, accuracy depends on manufacturer calibration data [1]. However, the cost of these tubes is less compared to Venturi tubes, especially long Venturi tubes. For flow tubes refer Fig. II/5.0.0-1.

To summarize, there are two important aspects:

- The accuracy in performance is highly dependent on the manufacturer data and calibration facility;
- Better PPL should be considered in conjunction with the higher upstream pipe length and lower discharge coefficient.

5.1.0 Lo-Loss Flow Tube

In 1961, the performance of the first and original Lo-Loss flow tubes, which were designed and marketed by the Penn Meter Company out of Philadelphia, was documented in an ASME paper, "Design and Calibration of the Lo-Loss Tube (61-WA-80)." [13]. As stated earlier, these meters are proprietary, therefore the description will be from the associated technical brochure.

5.1.1 FLOW ELEMENT DESCRIPTION AND APPLICATIONS

1. **Description:** This is a DP-producing flow element with low PPL and high accuracy, which is maintained over a wide range of flow rates [14]. It has a very short converging section and the throat is effectively missing (very narrow). Upstream tapping is immediately before the start of the converging section, as

Flow Tube: ***According to ASME flow tube is any head type flow element which does not follow Classical venturi. So, Dall tube is a flow tube. Flow tubes are three types.***

Type I: ***In these flow tubes the both upstream and downstream tappings are static tappings***

Type II: ***In these flow tubes, upstream tapping is corner tapping* and downstream tapping is static pressure tapping.***

Type III: ***In this design both upstream and downstream tappings are corner tapping****

**** Corner tapping:*** ***This tapping is placed very near the restriction. A corner tap senses pressure in a section where the velocity is changing direction and is not parallel to the pipe wall [1]. So any disturbance in upstream it is highly affected. Therefore requires more straight length.***

FIGURE II/5.0.0-1 Flow tube and corner Tapping.

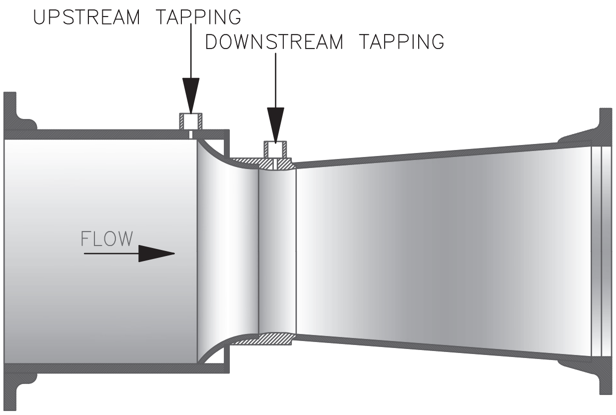


FIGURE II/5.1.0-1 Low-loss flow tube.

shown in Fig. II/5.1.0-1. A special characteristic of the meter is its flexibility of design. It can be manufactured with a wide range of materials.

2. **Application:** This meter finds its application in those cases where there is a wide range of temperature and pressure. As it can be manufactured from a wide range of materials it can be used in an aggressive process medium. This type of meter finds its application in power plants, refineries, petrochemical plants, etc. It is even used for custody transfer [14].

5.1.2 SPECIFICATION/DATA SHEET

Brief specification of the flow tube has been presented in Table II/5.1.2-1. In this table the basic technical and performance parameters pertinent to the flow element are presented. However, common parameters mentioned in Table II/4.5.0-1 in points 2–5, 7–9, 14–20, 22, and 23, are also applicable here, so following table should be read in conjunction with the above Table II/4.5.0-1 based on applicability.

5.2.0 Dall Tube

Although use of the dall tube developed in UK in 1950 is not popular in American market, it is still the most popular of the *various flow tubes* available internationally. The dall tube is often referred to as a shortened version of a Venturi tube. The dall tube is most popular for its low energy consumption, i.e., low PPL. When relative PPL is expressed as a percentage of DP range selected (produced), the head loss of the dall tube is almost half of that for a Venturi at the same beta ratio. The tap locations are mainly responsible for the apparently lower relative head loss expressed in % DP range (produced). The upstream tap is located just before the sharp projected part to create a momentum effect. This increases the upstream pressure reading. In contrast, the low-pressure tap is located in the so-called throat where the pressure is lowered. Therefore, the differential pressure reading gets higher. Thus, for relative head loss calculation the denominator is increased—hence relative PPL expressed as a percentage is reduced. However, this was achieved at the cost of its ability to accurately and reliably predict the discharge coefficient.

TABLE II/5.1.2-1 Specification of Lo-Loss Flow Tube (ref: Section 5.2.1 also)

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Pressure range	150 to 2500 ib class		User to choose
2	Temperature range	−250 to +650°C		User to choose
3	Mounting type	Between flanges/weld in		User to choose
4	Tapping	Upstream: immediately before the projected part of convergent section. Downstream tapping at narrow throat		
5	Accuracy	±0.25% FSD for flow calibrated meter		
6	Permanent pressure loss	Very low compared to other flow element. For beta ratio 0.35− 0.8 variation is only 7%−2% (of PD range selected) only		

For meter sizing [14] may be referenced.

The discharge coefficient is very much dependent on the beta ratio and Reynolds number. This flow element has certain advantages as well as disadvantages. This discussion starts with the description and features of this flow element.

5.2.1 DALL TUBE DESCRIPTION

A typical Dall tube is depicted in Fig. I/3.1.1-4. The Dall tube has a very steep convergent section, which has a diameter less than the pipe internal diameter, the buttress has been marked in the figure. Upstream tapping is located immediately before the buttress in the flow line as shown in Fig. I/3.1.1-4. It has almost no throat, but instead has an annular slot. After the annular space "throat," there is a divergent cone which also finishes at a step. A major feature of the Dall tube is the annular space between the "liner" and tube into which the flowing media pass to provide an average "throat" pressure [5].

In Dall tube (in fact this applies to the lo-loss flow tube also), the upstream tapping is taken immediately before the buttress or projection formed by the start of the converging cone. Referring to Fig. I/1.2.2-5, one can understand that at this point the convex nature of the streamlines is at its maximum, i.e., highest available pressure. At the throat (annular slot), there is a sharp change in the streamline profile from the converging to diverging sections. Looking at Fig. I/1.2.2-5 one can see that at this point there is maximum concave curvature. Thus the streamlined curvature head is ***subtracted*** from the "throat" pressure. So, on account of the two tappings, the differential head sensing will be larger. The annular slot is important. On account of this slot, there is no breakaway of the liquid from the wall at the throat and streamlining acts as a diverging jet. Thus the area of dead zone is at its minimum, so there is less chance for the formation of energy-consuming vortices resulting in a reduction in pressure. Because of the shorter length, friction loss will also be less. The combined effect of the two points discussed above is that there will be much less PPL. There is a flip side to the tube also. As the upstream tapping is located immediately before the buttress, any upstream disturbance will have a direct effect on measurement accuracy. This calls for higher straight length in the upstream side. Also, the Reynolds number effect and manufacturing complexity [5] are some of the disadvantages of Dall tubes.

The flow (q) can be derived from *DP* as per the following equation:

$$q = K\sqrt{DP}$$

where K is the element constant derived from mechanical parameters.

5.2.2 CHARACTERISTIC FEATURES AND APPLICATIONS OF DALL TUBES

This section covers the advantages/disadvantages and applications of Dall tubes.

1. **The advantages of Dall tube include:**
   - Proven flow metering technology;
   - No moving parts and robust design;
   - Very low permanent pressure loss—energy saving;
   - Accurate flow metering of clean gases and liquids;
   - Negligible wear and erosion;
   - Less maintenance/inspection required;
   - Accurate flow measurement;
   - Suitable for major process conditions;
   - Shorter overall lengths and less costly compared to Venturi tubes.
2. **The disadvantages include:**
   - Unpredictability of discharge coefficient;
   - Dependence of discharge coefficient on Reynolds number and beta ratio;
   - Longer upstream straight pipe length;
   - Not suitable for liquid flow with suspended solids;
   - Cavitations problem and manufacturing complexities.
3. **Application area:** The main application area for Dall tubes is in gas transmission pipe lines. Apart from this, the flow element is used in power plant applications, and hydrocarbon liquid and gas measurements.

5.2.3 SPECIFICATION/DATA SHEET

A brief specification/data sheet for a Dall tube is presented as Table II/5.2.3-1. However, common parameters mentioned in Table II/4.5.0-1 in points 2–5, 7–9, 14–20, 22, and 23 are to be considered applicable, so the following table shall be read in conjunction with the above table Table II/4.5.0-1—based on applicability.

While the Dall tube and other flow tubes are popular for flow measurement, the Pitot tube is another head type flow measuring element used mainly in gas applications. A short discussion is presented on these here.

stagnation pressure. The side hole(s) measures the static pressure in the parallel tube (which is closed at one end). By measuring the difference between these pressures, the dynamic pressure is obtained, which can be used to calculate flow speed—hence flow. Since the Pitot occupies a small portion of the pipe it inherently has much lower PPL. The process conditions necessary are discussed at length in connection with annubar in Section 7.3.1. Fig. I/3.1.1-5 shows a cross-section of a Pitot tube. We now look at Pitot tubes in more detail.

TABLE II/5.2.3-1 Specification/Data Sheet for Dall Tube (Mainly Available Data) (ref: Section 5.2.3 also)

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Available sizes	50 –1200 mm		
2	Pressure rating	Up to 150 lb pressure class		
3	Beta ratio	0.4–0.8		
4	Reynolds number	Should not be less than 10^4		
5	Pressure loss	~5% of chosen DP		
5	Turn down	10:1		
6	Accuracy	+3% uncalibrated +1% Calibrated		
7	Standard	ASME 31.3/PED-97/23/EC		

Data based on: Courtesy: Flow Stream Dall Tubes; for Top Side Flow Measurement, Solarton ISA, http://www.solartronisa.com/Products/dalltubes.aspx.

6.0.0 PITOT TUBE

The Pitot tube has been named after the French Scientist Henri Pitot in 1732. The Pitot tube is associated with wind tunnel experiments and airplanes to measure flow speed and are also used in process controls for flow measurement. The device consists of a Pitot tube inside or adjacent to a parallel tube closed at the end. The front hole of the inside tube is placed in the airstream to measure what's called the

6.0.1 BASIC PRINCIPLES OF PITOT TUBES

As stated earlier, in Pitot tubes fluid velocity is measured from the velocity, fluid flow is computed. Based on Bernoulli's energy equation, the velocity is also estimated from conversion of the kinetic energy of the flow into potential energy. As discussed in Chapter I, in Pitot tubes there is one narrow pointed tube facing the flow as shown in Fig. II/6.0.1-1. This tube is put inside

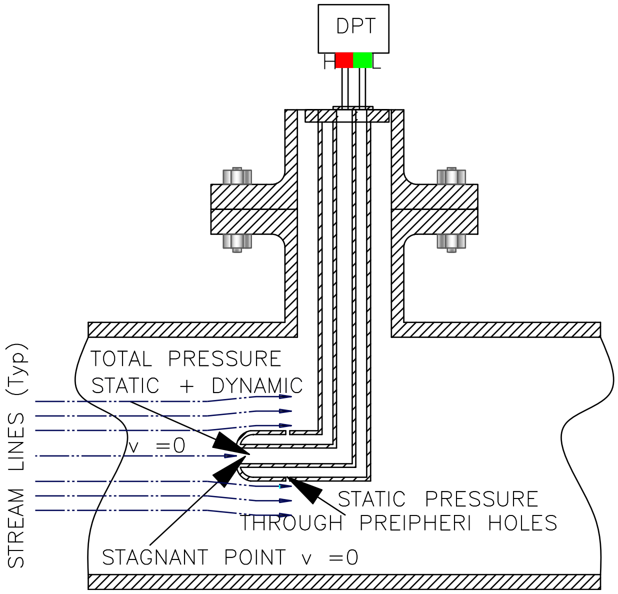


FIGURE II/6.0.1-1 Pitot tube principle.

another tube with a closed end. Therefore, when the stream line flow reaches the narrow inner tube the stream line velocity at this point goes to zero. The point (area) where velocity reaches zero is referred to as the stagnation point and is located at the Pitot tube entrance. The energy conversion takes place at this stagnation point. The tube enclosing the inner tube has a number of holes in the periphery to measure the static pressure of the stream line. At the Pitot tube entrance, i.e., at the stagnation point, since velocity is zero, kinetic energy is converted to pressure energy, and the pressure at this stagnation point is the total pressure constituted by static pressure and dynamic pressure (increase) due to conversion of kinetic energy to pressure energy. Thus there will be a difference in pressure between the inner tube and the closed external tube. Connections from both are connected to one differential pressure transmitter (DPT) to measure the pressure difference from which flow is computed. It is evident that the stream line with higher flow (i.e., velocity) will have higher kinetic energy. Therefore, for the same static pressure, the differential pressure will be greater, due to higher energy conversion. Therefore, the higher the flow, the higher will be the DP but this increase is not linear. While making the calculations it is necessary to consider the type of fluid, i.e., whether it is incompressible or compressible.

6.0.2 FLOW CALCULATIONS

Short discussions follow on flow calculation from the differential pressure discussed in the above subsection. Here we shall discover the velocity. Once the velocity is known, by multiplying this with the area one can gets volume flow rate. Both noncompressible as well as compressible fluids are covered.

1. **Noncompressible fluid:** For a horizontal pipe, one gets from the Bernoulli energy equation discussed in Chapter I

   $v^2/2g + p/\rho g = \text{constant}$; where v is velocity and p is static pressure.

   Evaluated at two different points along a streamline, one gets:

   $v_1^2/2g + p_1/\rho g = p_2/\rho g$; as at stagnation point velocity $(v_2) = 0$.

   or $v_1^2/2 + p_1/\rho = p_2/\rho$; Therefore

   $$v_1 = \sqrt{\frac{2(p_2 - p_1)}{\rho}} \qquad \text{(II/6.0.2-1)}$$

   At the stagnation point, the total pressure $P_{total} = P_2 = P_{dynamic} + P_{static}$ (refer to Section 6.0.1 above).

   So Eq. II/6.0.2-1 can be rewritten as

   $$v_1 = \sqrt{\frac{2(P_{stag} - P_{static})}{\rho}} \qquad \text{(II/6.0.2-2)}$$

2. **Compressible fluid (M < 1):** In connection with the sonic nozzle we came across the Mach number. The Mach number is defined as the ratio of fluid velocity by velocity of sound, i.e., $M = v/c$ where c is the velocity of sound. For subsonic compressible fluid: the $0.3 < M < 1$ relation stands. For a Pitot tube in subsonic compressible flow $(0.3 < M < 1)$, fluid, at the stagnation point the fluid is continuously compressed. This means that fluid is decelerated and compressed from a

free-state to an isentropic state. On account of this compression the density will be changed and for such case the relationship between pressure and velocity is a function of specific heat ratio κ. (=C_p/C_v as already discussed). The relationship can be obtained as:

$$v = \left[\left\{\left(\frac{P_{stag}}{P_{static}}\right)^{(\kappa-1/\kappa)} - 1\right\} \cdot (2\kappa/\kappa - 1) \cdot (P_{static}/\rho_{static})\right]^{1/2} \quad \text{(II/6.0.2-3)}$$

As there is a chance of interference and some flow deflection, it is necessary to include one compensatory flow factor/coefficient K_p used with the flow equations.

(On account of limited space, a basic derivation of the relation is beyond the scope of the book and any standard fluid mechanics book should be consulted.)

3. **Limitations:** There are a few practical limitations, these are:
   - If the velocity is small then the DP will be too low and there could be a measurement error due to instrument inaccuracies. Very precise instruments may be necessary.
   - When in compressible fluid $M > 1$ then fluid velocity will be a function of Pitot tube pressures, which in turn would be dependent on Mach number and specific heat ratio. For $M > 1$ there will be shock waves, and Bernoulli's equation, with which we started our discussion, will not hold good.

6.0.3 PITOT TUBE TYPES

Based on construction (and certain extent on performance), there are three types of Pitot tube; actually there are two types: single point Pitot and average Pitot tube. However, there are variations in the average Pitot tube. In certain Pitot tubes (like those from ABB, Emco) a number of holes appear in the upstream side to sense average impact pressure and in the downstream side they have a single hole to sense the static pressure. The type of Pitot tube, referred to as an averaging Pitot tube, will be discussed in this section. In contrast, Emerson, Systec & Dwyer (PAFS-1000) supply different type of averaging Pitot tube, often referred to as Annubar. In this type of averaging Pitot or Annubar, there are two adjacent pipes with a number of holes in each of them. One of the pipes is placed with the holes facing the flow to sense the average upstream impact pressure and the other tube senses the average downstream static pressure. This is referred to as an Annubar and is discussed in the next section.

6.0.4 PITOT CALIBRATION

The Pitot Venturi discussed later needs each case to have line calibration with known velocity to establish any measurement inaccuracy. The National Bureau of Standards (now NIST) can calibrate Pitot tubes on a carriage, which is drawn through stagnant air at a known velocity. Smoke is used to confirm that the air is stagnant—that there is no turbulence [1]. The National Institute of standard and Technology (NIST) also offers a dual test-section wind tunnel. There is also another method, known as point velocity calibration methodology. These methods are also offered by agencies like Colorado Experiment Engineering Station Inc. (CEESI), which calibrates instruments with traceability to NIST.

6.1.0 Single-Point Pitot Tube

A single-point Pitot is depicted in Fig. II/6.0.1-1. The description was given earlier while explaining the principles of operation of the Pitot tube, and so is not repeated. Typically, a Pitot gives a flow range of around 4:1, with accuracy ranging between 0.5% and 5% FSD.

6.1.1 DESIGN AND CONSTRUCTION DETAILS

Pitot tubes find their major industrial applications in gas/air flow in pipes, ducts, and stacks. Even in

open channels Pitot tubes are used for liquid measurements. Normally Pitot tubes facing the flow are beveled with about 15 degrees and extended inside by about 1−1.5 tube diameter, as shown in Fig. II/6.1.1-1, so that it is not highly sensitive to flow. However, such design is suitable for one-direction flow.

There are a number of design variations in view of the applications. In their design, the majority of Pitot tubes have a classical design of a hemispherical nose with a bend shaft. The majority of these are made of stainless steel so that they can be used for a wide variety of applications. Normally Pitot tubes are available with a range of diameters and lengths to suit various applications. Most are available for bidirectional flow measurement. There are some special designs, such as the telescoping Pitot tube from Dwyer. This can quickly and easily be adjusted for a wide duct insertion length so that it can be used as a replacement for up to almost five conventional fixed-length Pitots,

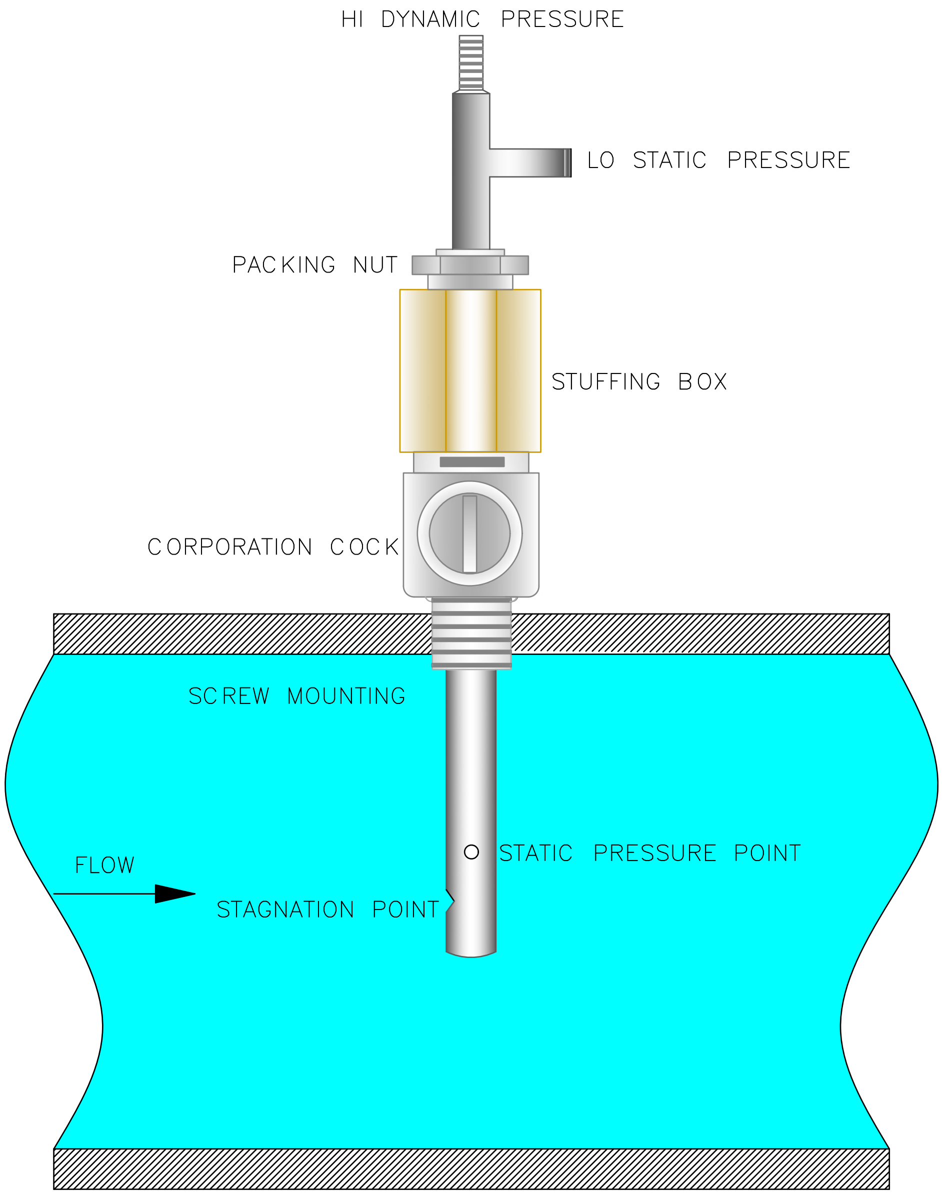


FIGURE II/6.1.1-1 Single-point Pitot with screw mounting tube.

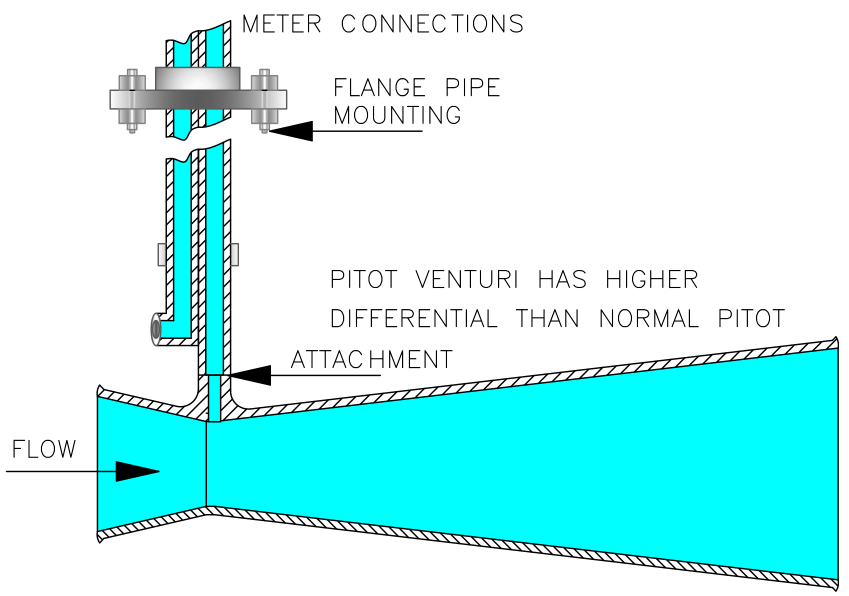


FIGURE II/6.1.1-2 Pitot Venturi.

e.g., model 166T from Dwyer. Another special design is the ASME style. Often Pitot Venturi are used to amplify weak pressure signals. A typical Venturi Pitot is depicted in Fig. II/6.1.1-2. Double Venturi Pitot designs are also often used. Usually the Venturi parts are attachable.

6.1.2 FEATURES AND APPLICATIONS

1. **Misalignment:** Less sensitive to misalignment up to 15°degrees.
2. **Leak-proof:** For leak-proof operations silver soldered connections are utilized.
3. **Wide range of size:** For telescopic design they can be used for wide pipe sizes.
4. **Application:** Their main application is for air flow/velocity measurement and control, including in aviation applications.

6.1.3 MOUNTING AND INSTALLATION

Single-point Pitot tubes can be mounted with a screwed connection as shown in Fig. II/6.1.1-1 or they can be mounted with a flange connection as shown by the Pitot (Venturi) tube with a flange shown in Fig. II/6.1.1-2. Pitot tubes can be mounted on a flanged plate with a screwed connection. In the case of a Pitot Venturi, the main tube can be inserted in the pipe by a screw connection and/or flange. Later the Venturi Pitot can be attached to the pipe. Such an installation is possible only in an empty pipe of duct sections. For a Pitot tube in a closed pipe and/or duct, approximately 10D and 5D straight length in upstream and downstream, respectively, are the requirements for single-point Pitot tubes.

6.1.4 PITOT TUBE SPECIFICATIONS

1. **General:** A short list of specifications pertinent to a single-point Pitot has been elaborated in Table II/6.1.4-1. However, in order to complete the specification, depending on applicability, points 2–5 and 18 of Table II/3.5.0-1 and points 22 and 23 of Table II/4.5.0-1 should also be included in the data sheet.
2. **Specific data:** For specific data, Table II/6.1.4-1 may be referenced.

TABLE II/6.1.4-1 Specification for Single-Point Pitot Tube (ref: Subsection 6.1.4.1 also)

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Insertion length	Up to 1800 mm with Total shaft length >2000 mm		Depends on tube diameter
2	Tube diameter	2–30 mm		
3	Extension length	With/without stiffner		
4	Mounting style/size	Screwed/flange/flange plate with screwed connections		
5	Process tapping connection	½″ or 3/8″ NPT/BSP thread		
6	Temperature compensation	Yes/no		
7	RTD connection	3 wire		
8	RTD mounting	Separate tube screwed		
9	RTD specification	Pt 100 Ω, inset tube 6 mm		
10	Fittings and accessories	Compression fitting, carrying case, mounting glands		

6.2.0 Average Pitot Tube (Not Annubar)

In most cases, the average Pitot tube presents the measurement of flow by measuring upstream and downstream average pressure differentials, by deploying two sets of perforated pipes. Such flow measurements are not carried out by a Pitot tube in the true sense. This is more properly known as an *Annubar* and has been discussed in Section 7.0.0 of this chapter. However, there is another kind of measurement. Unlike a typical single-point Pitot tube (being a point-velocity device), an average Pitot tube has multiple impact-sensing ports across the pipe diameter and one downstream pressure-sensing point. This produces an averaged differential pressure signal to compute the flow rate.

6.2.1 DESIGN AND CONSTRUCTION DETAILS

A distinguishing feature of this averaging Pitot in contrast with the single-point Pitot is that there is one outer tube with a number of impact pressure-sensing holes facing upstream that are positioned at equal annular points in accordance with a log-linear distribution [16]. This will help averaging of total pressure sensed by a set of upstream holes. This pressure represents the high-pressure component of the DP output. The low-pressure component or downstream pressure is sensed by a single hole through the outer tube but connected to the low-pressure chamber. Fig. II/6.2.1-1 may be referred to for the construction details and mounting options of an average Pitot. Like a single-point Pitot here also there are two separate concentric tubes. The only difference is that here the impact force is sensed by an internal tube. There is an outer impact force-sensing tube with several equally spaced holes facing the flow and averaging chamber. Also, there are separate internal low-pressure sensing holes connected to a chamber and a head for DPT connection. For bidirectional flow measurement such impact-sensing holes are in both directions (more like an Annubar) The shape of the sensor design is important here to get better performance.

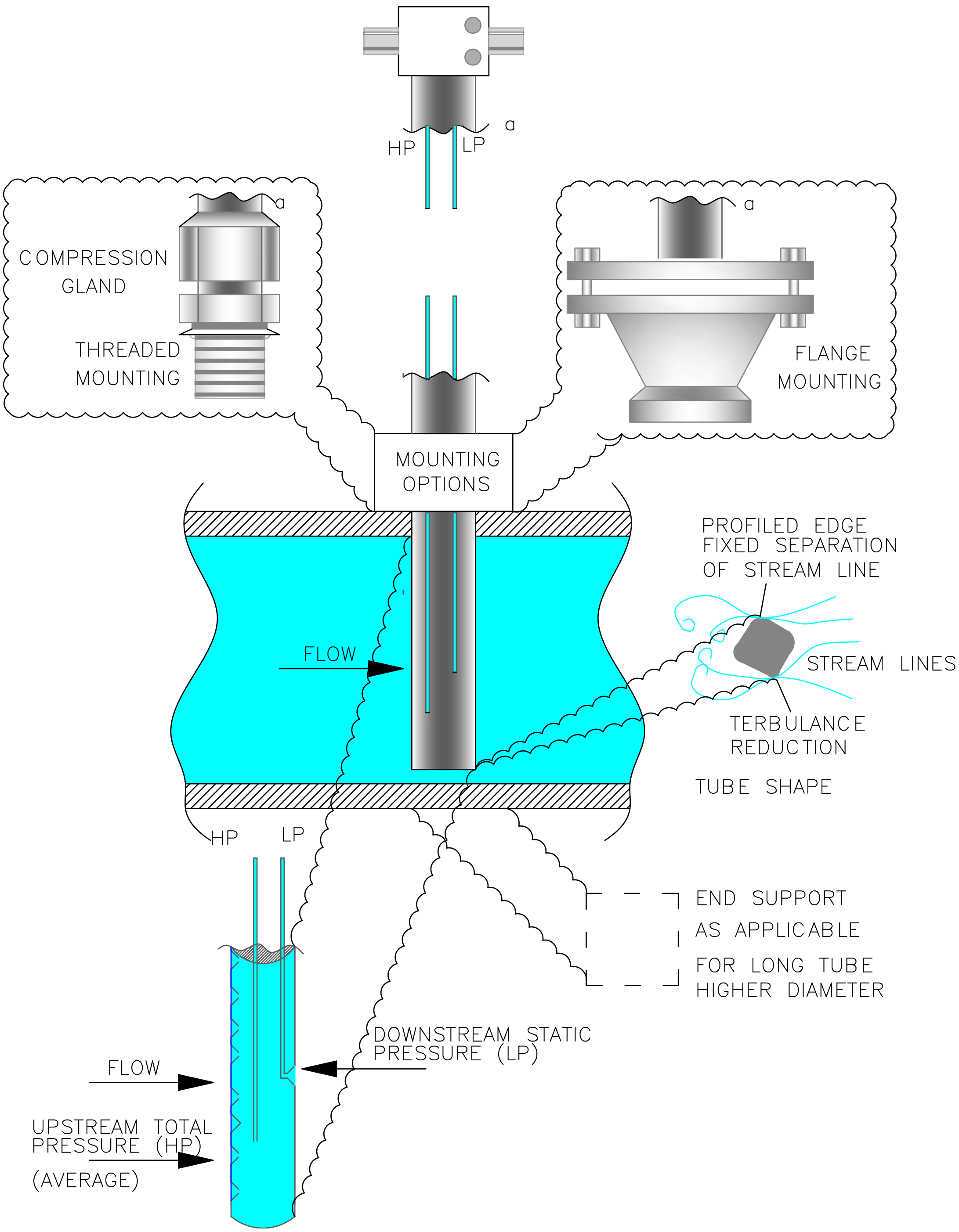


FIGURE II/6.2.1-1 Averaging Pitot. *Developed based on Flow Stream Dall Tubes; For Top Side Flow Measurement, Solarton ISA. http://www.solartronisa.com/Products/dalltubes.aspx; courtesy: ABB.*

There are diamond or other shaped profiled flat edges in the downstream side that help to get a fixed separation point in the flow streamlines as shown in Fig. II/6.2.1-1. Most of the tubes are manufactured as per international standards, especially for welding work and leak-proof testing. They are generally manufactured with stainless steel but other materials are also available.

Basically the Pitots are very easy to install as shown in the above figure. Most are available

TABLE II/6.2.1-1 DP Sizing Equation for Average Pitot Tube

Service	Associated Equations
For DP in KPa; P Absolute pressure in KPa; Volume flow q in m^3/h or Nm^3/h (compressible fluid); mass flow q_m in kg/h; ρ in kg/m^3 or kg/Nm^3 (compressible fluid); Temperature T in K; D pipe Internal Diameter in mm; K m Factor	
Liquid volumetric measurement in m^3/h	$6.4 \times 10^4 \times K \cdot \rho \cdot (q/D^2)^2$
Gas volumetric measurement in Nm^3/h	$2.4 \times 10^9\ K \cdot \rho \cdot (P/T)\ (q/D^2)^2$
Fluid mass flow measurement kg/h	$6.4 \times 10^4 \times K \cdot (1/\rho) \cdot (q_m/D^2)^2$

with provision for RTD insertion/mounting. This facilitates compensated flow measurement and easy connection to multivariable transmitters. There are some models of average Pitot tube which are withdrawable, namely, the following models: *FPD350.L6* and *FPD350.L7* from ABB. Basic calculation methods have been described in Section 6.0.2. Table II/6.2.1-1 shows the approximate calculating equation for DP sizing.

For DP selection one has to take into consideration the stress due to the maximum allowable DP. Therefore, with end support, higher DP selection is possible. As shown in the figure there may be requirements of bottom support for long and higher diameter support. Features and application areas of the instrument are discussed next.

6.2.2 FEATURES AND APPLICATIONS

On account of some distinctive features of the instrument it finds its applications in many industrial areas, in this section these are discussed.

1. **Features:** The following are the major features worth mentioning about the average Pitot:
   - *Profile:* Shape and profile are important to achieve fixed separation and get high rangeability/turndown;
   - *Accuracy:* Averaging of the impact pressure results in accuracy. It also offers long-term accuracy;
   - *Sizes:* Available for a wide range of pipe sizes;
   - *Pipe/duct:* Suitable for square or rectangular as well as closed and pressurized pipes;
   - *Operating conditions:* Available for wide pressure and temperature ranges;
   - *PPL:* Lower permanent pressure loss and energy (cost) saving;
   - *Cost:* Low installation and maintenance costs.
2. **Major application areas:** The average Pitot has a good number of applications, some of the major ones include:
   - Power plants;
   - HVAC plants;
   - On-/off-shore oil production;
   - Oil refineries;
   - Chemical plants;
   - Nuclear;
   - Food industries;
   - Water treatment;
   - Effluent treatment, etc.

   In these plants the major application fields are flow measurements of:
   - Natural gas;
   - Combustion gas;
   - Flue gas;
   - Hydrocarbon gas;
   - Coke oven gas;
   - Ventilation gas;
   - Hot air;
   - River water;
   - Sea water;
   - Waste water;
   - Cooling water.

6.2.3 MOUNTING AND INSTALLATION

In this section short discussions about the mounting and installation requirements of an average Pitot are discussed.

1. **Mounting:** There are a number of ways the average Pitot tube can be mounted with

TABLE II/6.2.3-1 Upstream Straight Length: Average Pitot Tube (Multiple of D) [16,17]

Type of Restriction Upstream	Same Plane	Different Plane	Remarks
90 degrees bent	7D	9D	90 degrees bent after 3D at downstream
Two successive 90 degrees bents	9D	14D	As above
Two successive 90 degrees bents in different planes	19D	24D	As above
2:1 or 1:2 Reducer or expander	8D		
Full open valve	24D		4D Downstream

a pipe. These are possible both in horizontal and vertical pipes. In major cases, screwed and flanged connections are used as shown in Fig. II/6.2.1-1 under mounting options. In most cases average Pitot tubes are available with provisions for temperature probe (RTD with inset tube) mounting. Normally the outer tube is meant to sense impact/total pressure as a single unit but for large lengths (say >5 m) these may be in two pieces [16]. Also, it is possible to get the in-line fitting types with end fittings suitable for Butt weld, flanged, or threaded fittings. In the case of in-line fittings the associated pipes are supplied with the instrument and pipe of the same material as that of the average Pitot tube [16]. For large pipes a bigger length of Pitot will be necessary, so in those cases longer and higher Pitot end supports at the pipe, especially for higher pressure applications, will be necessary. These end supports are available in screwed and weld connections. With end support higher DP selection is possible. As indicated earlier, retractable Pitot tubes are available with isolation valves, safety chains, and pressure chambers as necessary [16]. These retractable versions are available for screwed as well as flanged connections. In the majority of cases tilting and/or misalignment of ±5 degrees is allowed. In most cases it is suitable for direct DPT mounting (through oval flange connection) and in such cases an isolation valve or valve manifolds are also available. It is also possible to have impulse line connections.

2. **Installation and installation requirements:** As with mounting, for process connections screwed (male/female) and flanged ones are available. These can also be with needle/ball/gate valves. As stated earlier it is possible for direct DPT mounting. Also, quite frequently DPTs are connected through impulse line connections. In such cases installations similar to those depicted in Figs. II/2.2.4-1 and II/2.2.4-2 (or Figs. II/3.2.4-1 and II/3.2.4-2 or Figs. II/4.2.3-1 and II/4.2.3-2) may be followed based on relative locations of transmitters and flow element. Straight length requirements for average Pitot tube are also expressed in terms of pipe internal diameter (length of rectangular duct) "D." *Downstream* straight length requirements for an average Pitot are normally 3D (4D for open valve). *Upstream* straight length requirements for an average Pitot varies with restriction type and has been elaborated in Table II/6.2.3-1.

6.2.4 SPECIFICATION OF AN AVERAGE PITOT

1. **General:** A short specification pertinent to an average Pitot has been elaborated in Table II/6.2.4-1. However, in order to complete the specification, depending on applicability, points 2−5 and 18 of Table II/3.5.0-1 and points 22 and 23 of Table II/4.5.0-1 should also be included in the data sheet.
2. **Specific data:** For specific data pertinent to a single-point Pitot, Table II/6.2.4-1 may be referenced.

TABLE II/6.2.4-1 Specification for Average Pitot Tube (ref: Subsection 6.2.4.1 also)

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Insertion length	50 to <5000 mm		Basically pipe size. For higher size with end support
2	Tube diameter	13/25 mm		
3	Sensor material	Stainless steel/alloy C276/SS304L		
4	Mounting style/size	Screwed/flange/in line		
5	Process tapping connection	Screwed ½″ NPT/BSP, socket weld, flanged with/without isolation valve		
6	Process fluids	Liquid, gas, or steam		
7	Operating conditions	Max pressure 500 bar		
		Max. temperature: <600°C		
8	Temperature compensation	Normally yes with RTD		
9	RTD mounting and connection	Built in thermowell/screwed		
10	RTD specification	Pt 100 Ohm, with standard inset tube (6 mm)		
11	Fittings and accessories	Needle, ball, or gate valve, integral valve manifold, pipe for inline mounting, oval flange for direct transmitter mounting		
12	Performance	Accuracy ±1%		
		Repeatability ±0.1%		
		Turndown; 10:1		
13	Retractable facility	Possible/under pressure also		
14	Standard	Approval from international standards: BS, ANSI, ASME, ISO, and DIN standards		

6.2.5 AIR AND FLUE GAS MEASUREMENT BY AN AVERAGE PITOT TUBE

A short discussion has been presented below to show the application of an average Pitot tube for air and flue gas flow measurements. The advantages of average Pitot tubes over other flow elements include minimal PPL, low cost, and easy installation. The basic requirement of optimum combustion is the supply of a mass of (hot) air which is in stoichiometric balance with the mass of fuel—in fact BTU/ calorific value of the fuel. Therefore the importance of measurement of air flow in the duct cannot be overstated. Another issue associated with the measurement of air in the duct is leakage through an air heater making air flow measurement difficult due to dust. A special design average Pitot tube shown in

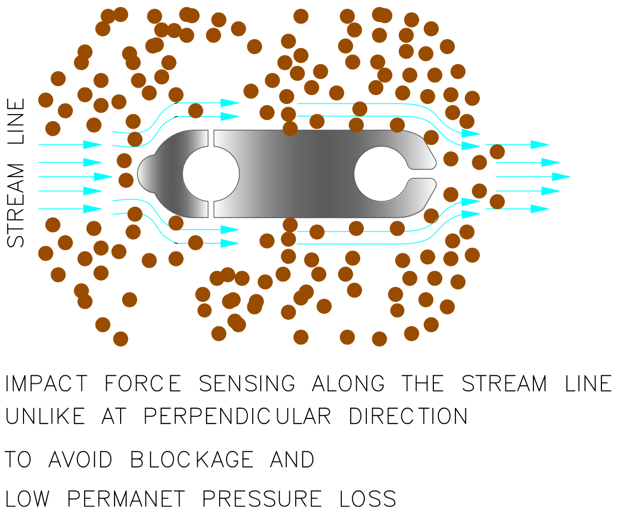


FIGURE II/6.2.5-1 Special average Pitot design and application. *Developed based on Pitot Bar Averaging Pitot Tube for Flow Measurements, Emco Controls; Product Brochure. http://www.emcocontrols.com/files/pdf/pitobar.pdf; courtesy: Eastern instruments.*

Fig. II/6.2.5-1 is a solution to this. In the average Pitot with special design (courtesy: Eastern Instrument—[18]) a notable exception to the plugging problem is the Pitot technology used here. In this design, the Pitot places its "high" port in line with the air flow and thus, has no impact ports. On account of this design, no purge system is required. This is used with a set of flow-straightening vanes. This design gives a plug-resistant flow conditioning system. With this design the required upstream and downstream straight duct requirements are minimal, with low PPL.

Another application area for an average Pitot is the measurement of flue gas flow in a stack. In a stack the flow is measured by a purging method. Also, there will be a temperature sensor integral with the flow element to take care of actual flow measurement. The main requirements for these elements are to be able to work at high temperature (even up to 1000°C) and for a large duct, such as 8000 mm. Normally these instruments are supplied with an "Auto" mode for purge control.

6.3.0 Krell Bar

Originally, the Krell bar was designed by Hartmann Braun, Germany, for measurement of flow of dirty gaseous fluids in large ducts/pipes. This could be conceived of as a flow element intermediate between a Pitot tube and an Annubar (a kind of average Pitot tube). It has similarities with Pitot tubes in the sense that like a single-point Pitot it also measures impact pressure with a single hole but the hole does not point toward the flow as shown in Fig. II/6.3.0-1. As the hole is perpendicular to flow direction, there will be more turbulence, hence straight length requirements will be less.

In fact there is a target plate which actually faces the flow and the hole is in line with the flow to ensure less dust to block the tube. Again like an Annubar it has a completely separate *adjacent* tube to sense the static or downstream pressure in a similar manner as it is sensing the impact pressure or total pressure. Unlike an Annubar, the tubes do not have equally spaced holes to take the average signal, so it did not become as popular as the single-point Pitot. However, because of the target plate and orientation of holes, it is very suitable for dust-laden gas flow measurement. When there is a requirement for purging it can be implemented in the flow element as shown in Fig. II/6.3.0-1. If this is not necessary, the purging (with air regulator) option may not be used. The rest of the operation is similar to Pitot measurement, i.e., measuring DP with the help of DPT to compute flow.

With this knowledge on flow measurement by Pitot, let us now examine operation of an Annubar (a kind of average Pitot tube).

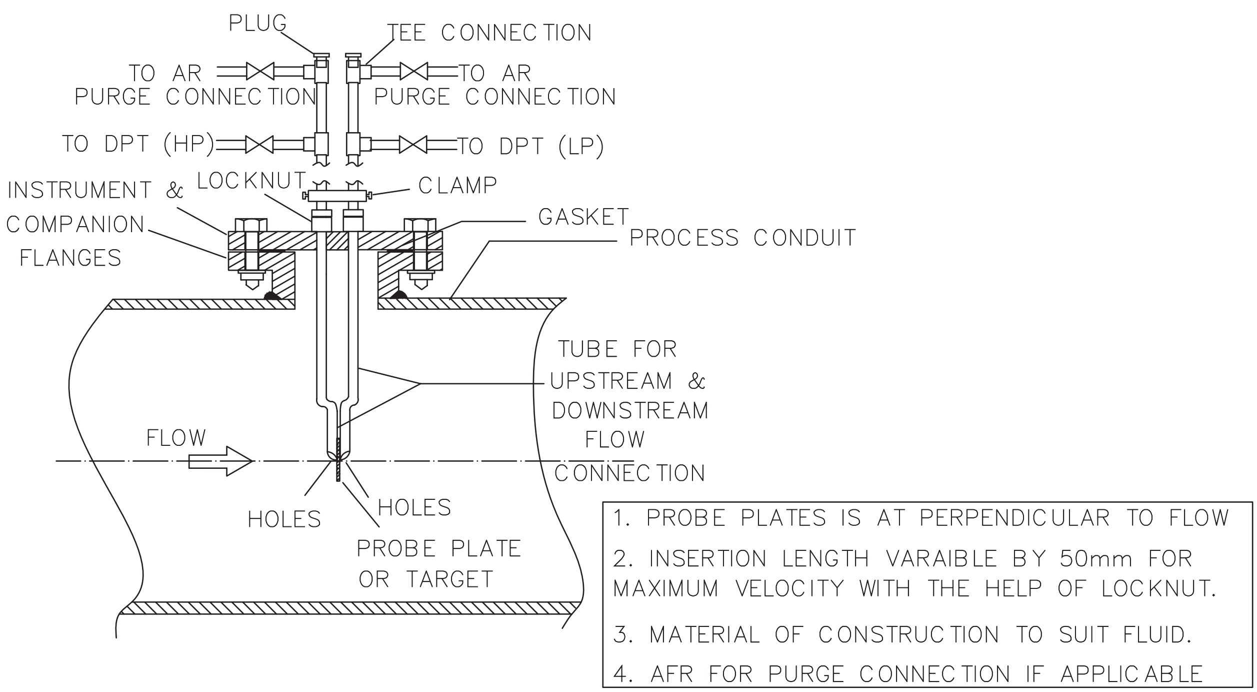


FIGURE II/6.3.0-1 Krell bar. *AR*, air regulator; *DPT*, differential pressure transmitter; *HP*, high pressure; *LP*, low pressure. *Courtesy: mechanical engineers Kolkata.*

7.0.0 ANNUBAR: AN AVERAGE PITOT TUBE (HP LP TUBES)

Basically, an Annubar is an average Pitot for flow measurement. As stated earlier, in order to distinguish this from the other types covered in Section 6.2.0, it is named the Annubar throughout this book. The basic principle of operation of this device has been discussed in Subsection 3.1.1.6 in Chapter I, and it has been illustrated in Fig. I/3.1.1-6. The discussion continues from this point.

7.1.0 Annubar (Average Pitot Tube) Description, Advantages, and Disadvantages

7.1.1 DESCRIPTION

The image in Fig. I/3.1.1-6 has been modified to develop Fig. II/7.1.0-1 and this is the starting point of this description. When fluid flow moves down a pipe it encounters a specially designed bluff body, the stream line impacts the bluff body when it loses velocity (hence from conservation of energy in line with Bernoulli's equation) and creates pressure greater than the pipe static pressure, i.e., static pressure plus impact pressure (to constitute the total pressure measured upstream). This is picked up by slots in the Annubar sensor. There are a number of such slots, like other average Pitots already discussed, to capture the flow profile across the bar to get more of the flow velocity profile, which will result in more accurate measurement of the flow rate. Unlike the other average Pitot discussed in Section 6.2.0, here downstream pressure is also measured by another tube with measuring slots along the tube length so that the average velocity profile in the downstream side can also be captured for precision measurement. At this point it is better to look at Fig. II/7.1.0-1. The tube profile is very important. There can be several tube profiles, each with a distinct advantage. In Fig. II/7.1.0-1 two typical profiles have been depicted. In one profile (courtesy of Rosemount) is a tee-shaped one. The other has oval-shaped tube profile (courtesy of Systec Germany). This tube profile is actually like a bluff body so that there will be fixed flow separation and there will be

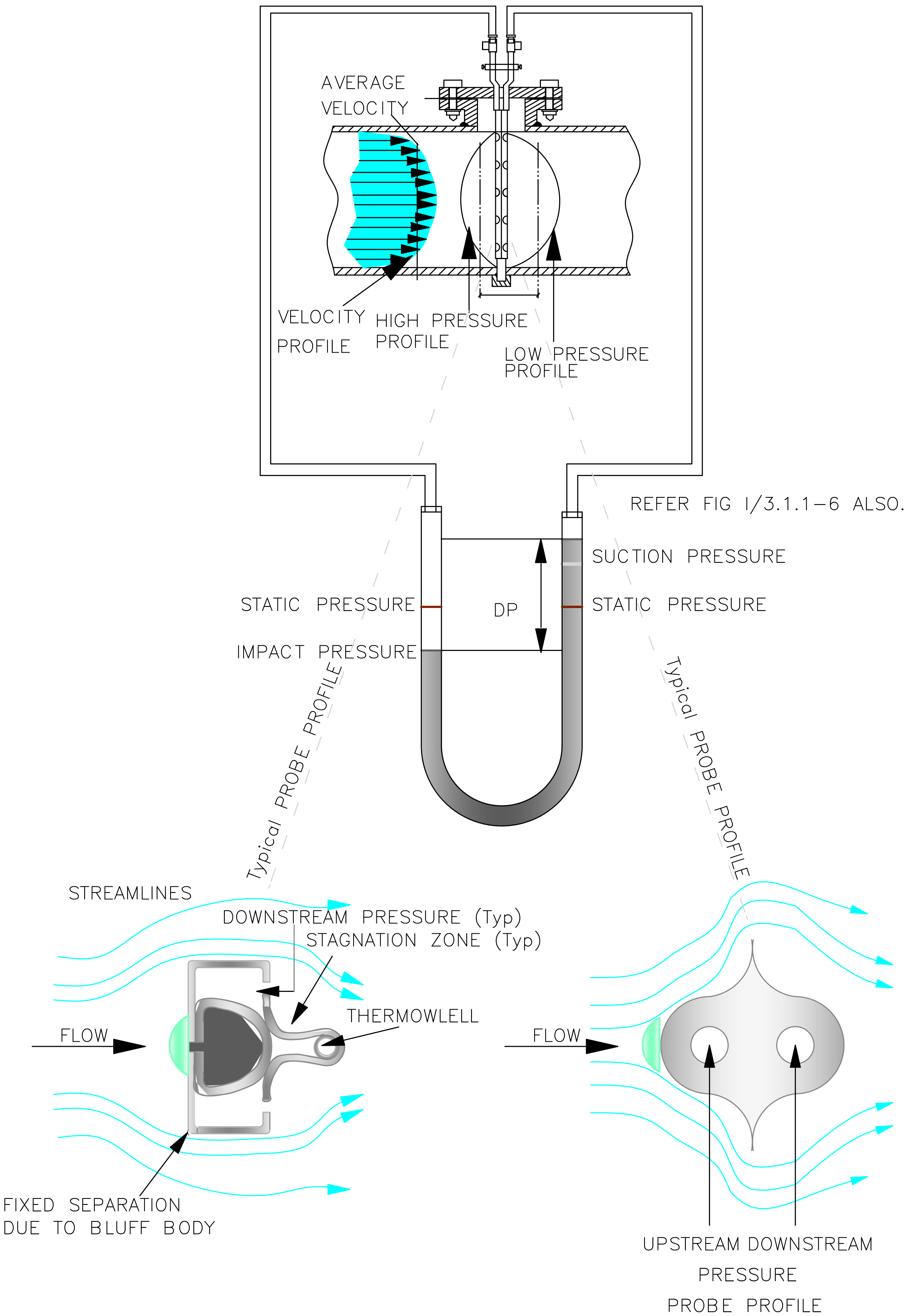


FIGURE II/7.1.0-1 Annubar details. *Developed based on Measuring Air Flow is Easy – Measuring Air Flow Accurately an Be Very Difficult; Combustion Air Flow Measurement, Eastern Instruments USA. http://easterninstruments.com/ActivePDF/Combustion%20Air%20Flow%20Measurement.pdf; courtesy: Rosemount, Developed based on Flow Metering for Gas Steam and Liquid; Deltaflow made by Systec, Systec Control, Catalog. http://www.systec-controls.de/files/deltaflow_brochure_en.pdf; courtesy: Systec.*

stability and long-term accuracy of flow measurement. On account of the bluff body, stream lines separate, creating blockage/suction immediately after the bluff body in the downstream side. This means that pressure at these points will be static pressure less the suction created. Therefore, downstream pressure sensed by downstream slots of tube will see less static pressure. Therefore when upstream and downstream tubes are connected to a manometer (DPT) it will see DP = total pressure − downstream pressure, i.e., total (static + impact) pressure − downstream (static − suction) pressure. So, DP = impact + suction pressure. Hence higher DP will be available for the same flow, when compared to an ordinary Pitot. This has been precisely shown in Fig. II/7.1.0-1 (top).

7.1.2 ADVANTAGES AND DISADVANTAGES

1. **The advantages of an Annubar include:**
   - Very low permanent pressure loss due to small area;
   - Integral transmitter mounting is possible;
   - Integrated temperature probe is possible;
   - *Hot tapping:* Insertion/installation is possible without process shutdown;
   - Retractability possible.
2. **Disadvantages of an Annubar include the following:**
   - It is not suitable for highly viscous fluid;
   - It is mainly suitable for clean fluid only.

7.2.0 Flow Element Calculation

Unlike a single-point standard Pitot, which measures the impact pressure of the velocity flow profile at a single point, with an Annubar, the impact pressure is sensed on the front of the device as the flow is brought to rest (stagnated) by the bluff body. Fluid velocity is not constant across the pipe cross-section (velocity is typically higher in the middle than on the edges due to viscosity and pipe friction effects discussed in Chapter I) as shown in Fig. II/7.1.0-1. Therefore, the velocity of the fluid with a single point can cause significant measurement errors. Obviously, multiple ports on the front side of an Annubar allow measuring the average impact pressure resulting from the flow profile for more precise and accurate measurement of flow rate. The downstream pressure is typically sensed on the back or on the side of the Annubar. For an Annubar there exist many shapes of bluff body or tube profiles that offer a variety of performance advantages.

The cross-sectional shape of the tube and the location of the sensing ports are important factors for the level and stability of the DP signal and the overall strength of the differential pressure, which is related to flow rate calculations and hence accuracy. Based on Bernoulli's equation, the velocity is determined. The flow rate is calculated by multiplying this velocity by the cross-sectional area of the pipe. Since it plays such a key role in the flow rate calculation, the area of the pipe, and so the diameter of the pipe, must be precisely measured for accurate flow measurement [19].

The flow can be determined from the following equation in simplified form without taking density variations due to pressure, etc.

From Eq. II/6.0.2-2 one gets the relation between DP and velocity as:

Velocity $v = \sqrt{2DP/\rho}$. So volume flow q = area* velocity or $q = \pi D^2/4.v$ or

Volume flow

$$q = K\varepsilon\pi\left(D^2/4\right)\cdot\sqrt{2DP/\rho} \qquad \text{(II/7.2.0-1)}$$

where D is pipe ID; ε is expansion factor (liquid = 1); and K is flow element coefficient which is related to probe-specific resistance c efficient.

Mass flow

$$q_m = K\,\varepsilon\,\pi\left(D^2/4\right)\cdot\sqrt{2DP\rho} \qquad \text{(II/7.2.0-2)}$$

Here rho is the density in the flowing condition. When variations in density with pressure and temperature or for flow at standard conditions are necessary calculations are performed in line with Eq. II/6.0.2-3.

7.3.0 Design Details

In this section, a brief discussion on fluid requirements and designed details about Annubar are presented.

7.3.1 PROCESS CONDITIONS

Some necessary process conditions discussed here for Annubar are also applicable for Pitot tubes discussed in Sections 6.1.0 and 6.2.0.

An Annubar can be used in all fluid forms, including liquid, gas, and steam. However, the conduit must be completely filled with fluid. For partial fluids, measurement is not possible except by special arrangements (e.g., using a siphon). The fluid for measurement must be single-phase—in two-phase fluids this measurement is not valid. Also, there must be turbulence in the fluid, measurement of fluid with a Reynolds number less than approximately 3200 is not possible. It is possible to measure liquids with some bubbles, or gas with dust. To avoid blockage with dust, programmable purging is not uncommon. Also for dust-laden gas, at times automatic purging arrangements are used. For steam applications, condensate pots should be used to avoid hot steam crossing the DPT. In the case of a condensate pot, steam pressure is transferred to the DPT via a water column through the condensate pot.

7.3.2 TUBE/BLUFF BODY PROFILE

Unlike a conventional Pitot tube, in Annubar measurement a bluff body or tube system with a special profile is used. The fluid divides when it finds an obstacle in current fluid that is nearly uniform. In Chapter I it has been discussed that, when fluid finds an obstacle, the stream lines separate. With the help of a specially designed bluff body such separations are made fixed for precision measurement. A few such bluff body shapes are shown in Fig. II/7.1.0-1. There can be other types, such as diamond-shaped or round-shaped. All these designs help ensure that dividing in current fluids is fairly uniform. Some characteristic features of these profiles are discussed here. Optimized probe profile and high-precision manufacturing strongly influence the measurement's precision. The following are the major benefits available from these specialized profiles:

- Absence of drift;
- Precision;
- Long-term stability;
- Reliability.

These profiles are developed and optimized through extensive testing [20]. In a tee-shaped bluff body, the upstream surface is flat with a rectangular slot, which helps to create a fixed separation point to improve performance over a wider flow range. On account of the shape there will be stagnation zones on the back side of the tee-shaped Annubar sensor. This helps to reduce the noise and measurement inaccuracies that lead to process variability. The flat upstream surface of the tee-shaped Annubar sensor creates a fixed separation point that improves performance over a wider flow range [19,21]. The diamond-shaped profile helps in achieving high accuracy, whereas the round-shaped one helps in DP measurement precision [22].

7.3.3 PRESSURE AND TEMPERATURE MEASUREMENT AND COMPENSATION

As most of the use of Annubar is for compressible fluid, it is necessary to have temperature and pressure compensation to take care of density variations with temperature as well as pressure. This naturally calls for temperature and pressure measurement. Unlike other flow elements like the orifice/nozzle etc. normally these do not use separate measurement systems. In most cases they are integrated with the flow elements. Also, on account of the special bluff body shape, they are accommodated within the bluff body (e.g., the temperature probe in a tee-shaped bluff body is accommodated at the back side, while in a diamond-shaped bluff body design it is accommodated between the two pressure-sensing tubes). In most cases three wire RTDs are used as temperature probes. As such, static pressure is

an inherent measurement in the system. This also helps in directly connecting the signals to multivariable transmitters. Some designs offer an integrated flow meter option with a multivariable transmitter (e.g., Rosemount). This type of design helps in avoiding impulse lining and hence less chance of a leakage.

7.3.4 PERMANENT PRESSURE LOSS

As discussed earlier in connection with the Pitot, Annubar occupies a small portion of process flow in the pipe and hence permanent pressure loss is minimal. Therefore, there will be energy savings.

7.4.0 Annubar Mounting and Installation

Annubar mounting is similar to what was discussed in Section 6.2.0.

7.4.1 ANNUBAR MOUNTING

The Annubar can be mounted with the pipe through a mounting channel by screwed connections or a flange connection as detailed in Fig. II/7.4.0-1. A weld in stud with cut ring, weld in stud with flange, and quick lock connections are quite common [20]. In the figure both options are shown for orientation. In the conduit a pipe may be fixed for connection with the instrument. There are also other options. For larger sizes end support may be necessary, depending on size, length, and application. As stated earlier and shown in Fig. II/7.4.0-1, the secondary instruments may be separate with a transmitter connected by an impulse line or they could have an integrated transmitter.

7.4.2 ANNUBAR MOUNTING ORIENTATION

This discussion starts with Fig. II/7.4.0-1. In this figure it is shown that there are different orientations for different fluids, as well as for horizontal and vertical pipes. In all cases it is desired that the Annubar is always filled with the fluid. In the case of steam this is achieved through a condensate pot. In connection with this, Section 7.3.1 may be referenced. Another issue is that side-mounting is preferred even in liquid so that dirt can be avoided to some extent.

1. **Liquid:** In the case of liquid it is desired that the Annubar is filled with liquid and entrapped gas if any is vented through the conduit, so orientation shall have a slightly downward slope toward the transmitter. In extreme cases it could be vertical with the transmitter below.
2. **Gas:** In the case of gas it is the reverse, so that entrapped liquid is drained toward the conduit, meaning downward slope toward the conduit. In extreme cases it could be vertical with the transmitter at the top.
3. **Steam:** This is similar to gas, except here vertical orientation is avoided so that in the case that the main conduit is empty then condensate may be drained. So, for steam side connections are better, to avoid draining.

7.4.3 TRANSMITTER CONNECTION

For DPT or multivariable transmitter connections weld end, ½″NPT/BSP thread, flange, oval flanges are also available. Often these are available with a needle, ball isolation valve, or three-valve manifolds. It is *not uncommon* to use a spool piece connection for an Annubar. Normally, in the case of integral transmitters, the Annubar is connected with the transmitter through a three-valve manifold. For compressible fluid there should be connections for pressure and temperature compensation. In the case that a multivariable transmitter is used all these are connected directly to the transmitter. In instances where an integral transmitter is not used then there shall be impulse lines for transmitter and pressure connections. For an impulse line connection, high and low pressure points of Annubar may be considered as source points and from their

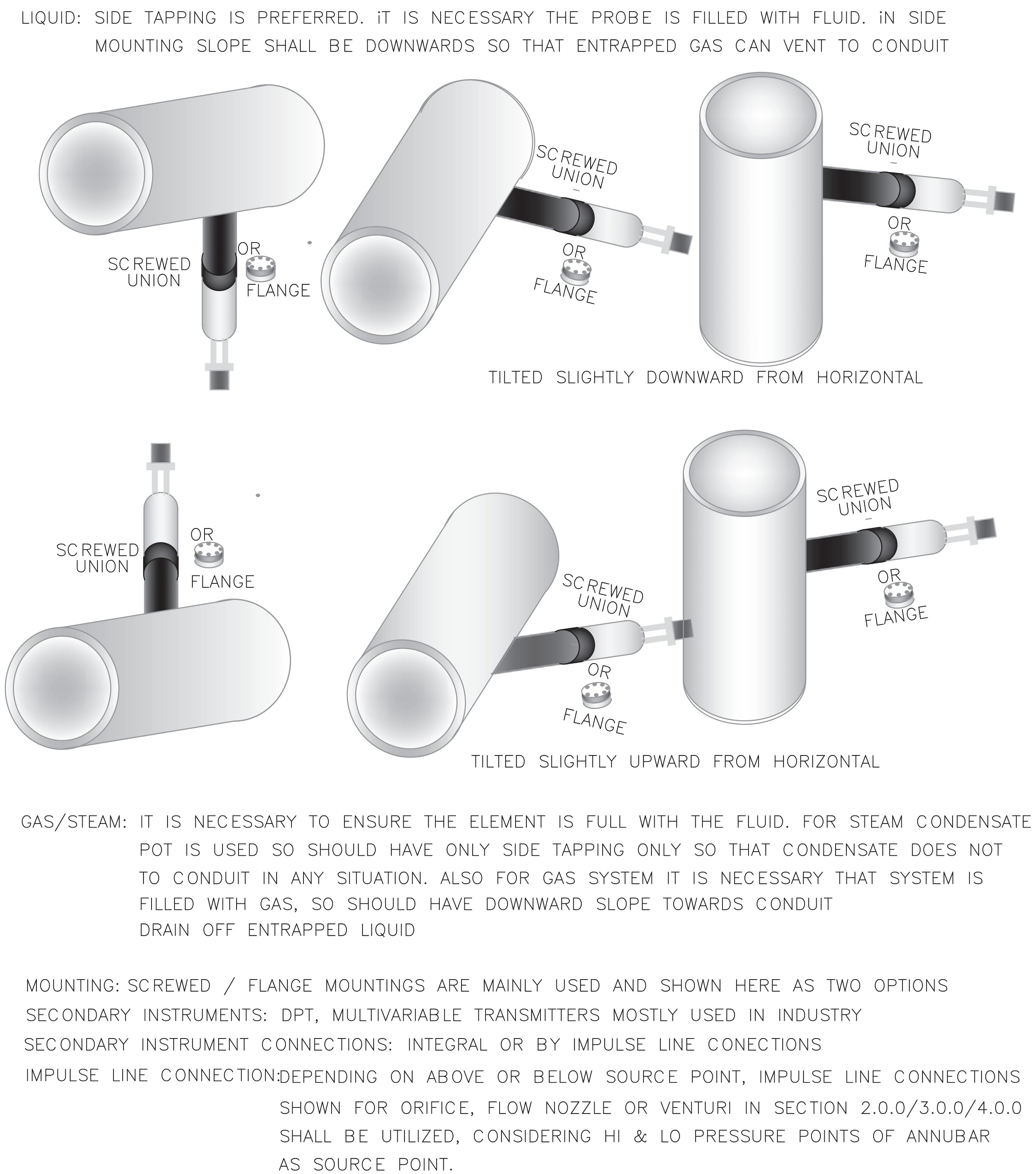


FIGURE II/7.4.0-1 Annubar mounting and orientations.

impulse lines are installed/laid. Depending on whether the source point is above or below the transmitter impulse line installations shown in connection with the orifice/nozzle/Venturi, Sections 2.0.0, 3.0.0, or 4.0.0 may be followed based on the applications pressure rating for the fittings used. As these installations are similar the details are not repeated here. Another

interesting feature is that an Annubar can be installed in the pipe without the need for process shutdown by means of hot-tap or wet-tap methods [19].

7.4.4 STRAIGHT LENGTH REQUIREMENT

The straight length requirements (the distance represented by A) for various obstructions in the upstream of the Annubar are given in Table II/7.4.0-1. With the use of a flow straightener/conditioner, such requirements could be reduced (distance represented by A′). The distances of the flow straightener from the Annubar and obstructions are represented by C & C′, respectively. The downstream straight length from the Annubar is represented by B. For clarity, this is illustrated in Fig. II/7.4.0-2. This figure is used as a reference for Table II/7.4.0-1. Normally, the downstream requirement (B) does not change and it is approximately **4D**, when D is the pipe ID based on which all dimensions are tabulated in Table II/7.4.0-1.

7.5.0 Annubar Specifications

7.5.1 GENERAL SPECIFICATIONS

A short specification of an Annubar has been elaborated in Table II/7.5.2-1. However, in order to complete the specification, depending on applicability, points 2−5 and 18 of Table II/3.5.0-1 and points 22 and 23 of Table II/4.5.0-1 should also be included in the data sheet.

7.5.2 SPECIFIC DATA

Specific data: For specific data Table II/7.5.2-1 may be referenced.

TABLE II/7.4.0-1 Straight Length Requirements of Annubar (Multiple of D) [20,23]

Obstruction Type	~Accuracy (%)	In Plane A	Out of Plane A	A′	C	C′
Single elbow	1	8	10	8	4	4
Double elbow	0.5	11	16	8	4	4
Reducer/expander	0.5	12	12	8	4	4
Expander	0.5	14	14	7	3	3
Valve (partial open)	0.5	30	30	8	4	4

Accuracy in %FSD; If proper lengths of straight run are not available, position the mounting such that 80% of the run is upstream and 20% is downstream [23]. All data are approximate values.

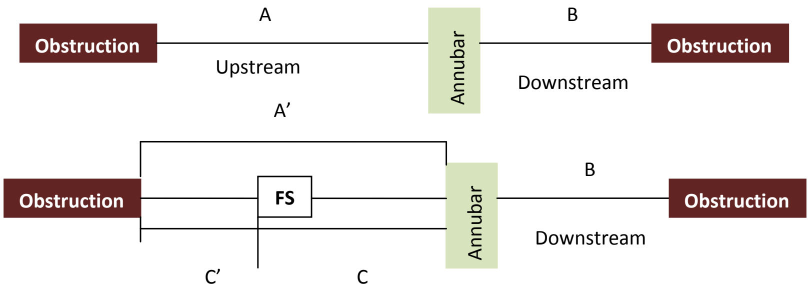


FIGURE II/7.4.0-2 Straight length requirement of Annubar.

TABLE II/7.5.2-1 Specification for Annubar (Ref: Section 7.5.1 for other data)

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Insertion length (line)	50 to <2500 mm		Basically pipe size. For higher size with end support
2	Tube diameter	14/26/50 mm	Depending on line size and Reynolds number varies with sensor type	
3	Sensing materials	SS316/alloy C276/SS 304L		
4	Mounting style/size	Screwed/flange/spool piece		
5	Process tapping connection	Screwed ½″ NPT/BSP, compression fitting, socket weld, flanged with/without isolation valve		
6	Process fluids	Liquid, gas, steam		
7	Operating conditions	Max pressure rating up to 2500 for remote transmitter; integral transmitter class 600 lb, 500 bar		
		Max. temperature: <600°C		
8	Temperature compensation	Normally yes with 3/4 wire RTD		
9	RTD mounting and connection	Built in thermowell/screwed		
10	RTD specification	Pt 100 Ohm, with standard inset tube (6 mm)		
11	Fittings and accessories	Needle, ball, or gate valve, integral valve manifold, pipe for inline mounting, oval flange for direct transmitter mounting		
12	Mounting materials	CS(A105)/SS 316/chrome moly steel		
13	Flow calibration	Yes for Factor K Instrument constant		
14	Certification	Material test certificate and other calibration certificate with traceability		
15	Performance	Accuracy ±0.75%		
		Repeatability ±0.1%		
		Turndown; 10:1		

8.0.0 SPECIAL HEAD TYPE FLOW ELEMENTS

Head type flow elements, like the V-cone and elbow type, have some special properties that distinguish them from conventional types. Very popular orifice plates have a central opening with some restriction to the flow in the peripheral sides. The V-cone is the opposite of that. In the V-cone, the obstruction is at the center and it is free in the periphery side, which creates a special flow element. The elbow is a very common pipe fitting, when fluid passes through them there will be different forces acting on the fluid layers, namely, the outer and inner layers. This creates DP which is measured to compute the flow. It is special in the sense that in all cases it can be only deployed when there is an elbow in the pipe. In this section the V-cone and elbow as head type flow elements are discussed.

8.1.0 Venturi Cone (V-Cone) Head Type Flow Element

The Venturi cone, better known as the V-cone, head type flow element consists of a cone that is positioned in the center of the metering conduit as shown in Fig. I/3.1.1-9. This means that, like an orifice plate, the V-cone reduces the cross-sectional area available for the process flow but in the reverse manner. Therefore, due to this restriction, there will be a low-pressure region downstream of the flow element. Hence there will be differential pressure with respect to upstream pressure (measured slightly upstream of the V-cone). Hence, the square root of the DP will be proportional to flow. In an orifice the sides are closed and the center is open. In contrast, here the center has an obstruction to flow and the sides are open. This is the major construction difference, which also causes a functional difference. In Chapter I it was shown that in the case of a low Reynolds number the velocity profile is somewhat like a parabola (unlike the square in turbulent flow) in a V-cone as it interacts with the high-velocity core at the center, through the obstruction, so it tries to flatten the center velocity and so at the stream near the wall, velocity increases. This conditions the flow and the system will then have a uniform flow profile like in a fully developed flow. On account of the central opening of the orifice this is not possible. Also, on account of the smooth contour of the V-cone, there is much less chance of erosion due to dirty fluids as happens in a square edge orifice.

8.1.1 WORKING PRINCIPLES

The theory behind the V-cone is not new, but has been in existence for a century. The V-cone is a head type flow element or differential pressure flow element; therefore, it is a working principle that stands on the footings of Bernoulli's theorem. As has been discussed in Chapter I at length, for a constant flow, the pressure in a pipe is inversely proportional to the square of the velocity in the pipe—meaning that whenever there is loss of velocity head, there will be an increase in the pressure head that is proportional to the square of velocity loss. In the case of a V-cone, when the fluid at pressure (say P_1) approaches the V-cone meter it faces the constricted area of the V-cone, and so the fluid velocity increases (in the wall side), and as per Bernoulli's theorem fluid pressure drops (to, say, P_2). Both the upstream pressure (P_1) and downstream pressure (P_2) are measured at the V-cone's taps using DPT. The DP created by a V-cone will increase and decrease exponentially with the flow velocity [24]. Because of the shape of the V-cone, the constriction takes up more of the pipe cross-sectional area, hence more DP will be generated for the same flow rate The beta ratio for V-cone is given by

$$\beta = \left(1 - d^2/D^2\right)^{0.5} \qquad \text{(I/8.1.1-1)}$$

where d is the diameter of the largest section of the V-cone and D is the pipe ID.

These are shown in Fig. II/8.1.1-1.

V-cone geometry is quite different from other conventional DP meters. In V-cone obstruction/restriction is at the center of the V-cone device, which is centrally placed in the pipe. This forces the streamlines in the center of the pipe to flow

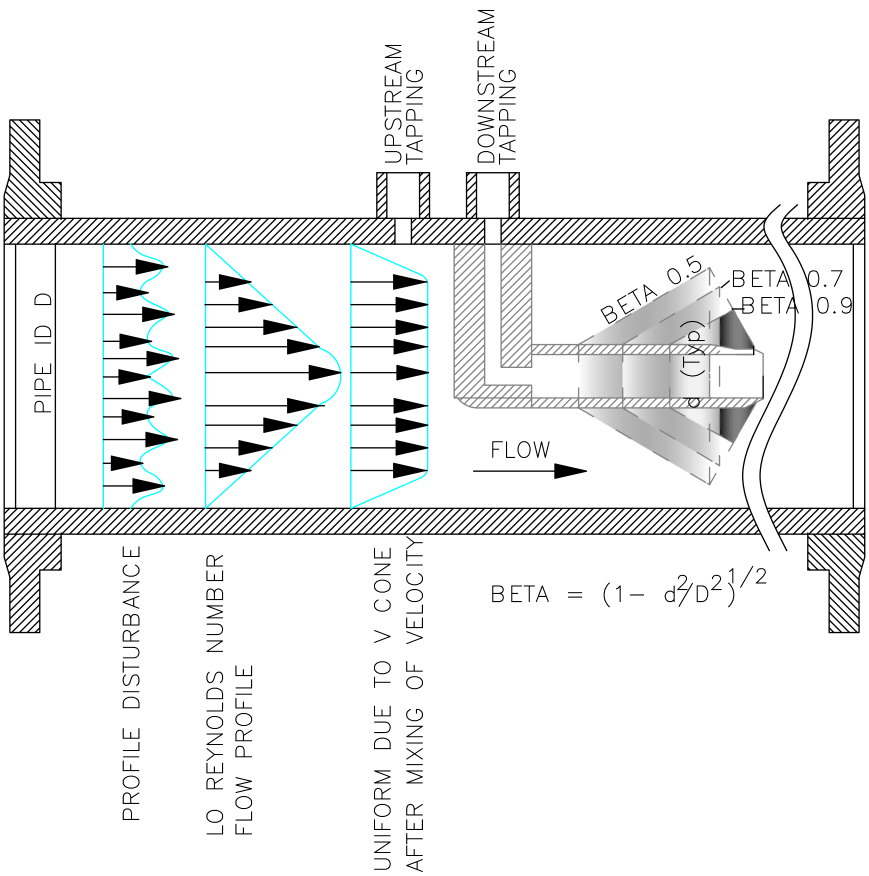


FIGURE II/8.1.1-1 V-cone operation.

around the cone. In order to understand the performance of the V-cone, one needs to understand the velocity/flow profile in a pipe, as discussed in Chapter I. As the cone is positioned in the center of the pipe, it interacts directly with the "high-velocity core" of the flow discussed earlier. Therefore, on account of the V-cone, there will be a mix of high-velocity core with the lower-velocity flows *closer to the pipe wall*. On the other head type flow elements, such as the orifice, flow nozzle, Venturi, etc. there are central openings, so there is no interaction with the high-velocity core. Thus this is an important advantage to the V-cone at a lower *flow rate/low Reynolds* number as discussed earlier. In view of this it is possible for the V-cone to interact with the highest velocity in the pipe, with the V-cone never losing useful DP signal, like other DP meters [24]. Also, with any *disturbance* in flow, due to an upstream obstruction, the effect is minimal in the case of V-cones. The V-cone overcomes this by reshaping the velocity profile by mixing. The contoured shape and position in line are responsible for such a benefit.

Now let us discover how to get flow calculations and d values for V-cones.

8.1.2 SIZING AND FLOW EQUATION

At the initial stage of the discussions it was stated that like any other head type flow meter the flow equation is derived based on Bernoulli's equation. When the discussion on flow equation derivation is recalled one would find that the beta ratio came from the area ratio of the restricted area by the pipe flow area. Similarly, when the same is applied one can derive the equation for beta for a V-cone. With reference to Fig. II/8.1.1-1, one can see that if the largest diameter of the V-cone is "d" then the minimum restricted area through

which flow can pass is given by total pipe flowing area minus the area obstructed by the V-cone with the largest diameter. Therefore,

Restricted area for flow $= \pi D^2/4 - \pi d^2/4 = \pi/4\ (D^2 - d^2)$.

Therefore area ratio $= \pi/4\ (D^2 - d^2)$: $\pi D^2/4$

Therefore,

$$(\beta)^2 = \left(D^2 - d^2\right)/D^2 \quad \text{or} \quad \boldsymbol{\beta} = (1 - \mathbf{d}^2/\mathbf{D}^2)^{0.5} \qquad \text{(II/8.1.2-1)}$$

Having defined beta in Eq. II/8.1.2-1, now one can have a look at the generalized flow Eq. I/2.1.8-1 and rewrite the same in terms of pipe ID as

$$Q_m = \mathbf{q_m} = \mathbf{C_d} \cdot \boldsymbol{\varepsilon} \cdot \boldsymbol{\pi} \cdot \mathbf{D}^2/4 \cdot \boldsymbol{\beta}^2 \Big/ \left(1 - \boldsymbol{\beta}^4\right)^{0.5} \cdot (2\boldsymbol{\Delta}\mathbf{p} \cdot \boldsymbol{\rho})^{0.5} \qquad \text{(II/8.1.2-2)}$$

where Q_m (ISO symbol) $= q_m$ (used in the book) = mass flow in kg/s. D-pipe ID in meters; ε expansion factor; ρ = density kg/m^3 C_d discharge coefficient (C in ISO); Δp = differential pressure in pascal.

From here the volume flow can be derived by dividing Eq. II/8.1.2-2 by the density. Now the volume will be in m^3/s. As the pressure temperature varies, it is necessary to convert this volume into cubic meters per second. Therefore, the temperature−pressure correction as already discussed in Chapter I will be used.

So,

$$q_v\left(Nm^3/s\right) = q_v\left(m^3/s\right) \cdot \left[\left(P/P_N\right) \times \left(T_N/T\right)\right] \qquad \text{(II/8.1.2-3)}$$

The gas expansion factor is given by [24]:

$$\varepsilon = 1 - \left(0.649 + 0.696\beta^4\right) \cdot \frac{\Delta p}{\kappa \cdot p} \qquad \text{(II/8.1.2-4)}$$

where κ is the fluid isentropic exponent at the flowing condition. For liquid $\varepsilon = 1$.

(ISO 5167 symbols are used in most cases.)

Pressure loss is given by [24]:

$$\mathbf{PPL\%} = \mathbf{100} \times (\mathbf{1.3} - \mathbf{12.5}\boldsymbol{\beta}) \qquad \text{(II/8.1.2-5)}$$

8.1.3 FEATURES AND APPLICATIONS

In many ways the V-cone offers a number of features that make it the preferred choice. A few advantages and limitations are listed below.

1. **Advantages offered by V-cones include the following:**
   - *Wide range of fluid applications:* gas/air, steam, liquids;
   - Wide Reynolds number (up to 8000) shows perfect square root, below that it also works but the relationship needs proper interpretation;
   - Short straight runs. When compared with other DP flow element it offers less straight length requirements, e.g., 20% of the total straight length is required for an orifice plate;
   - Stable differential pressure signal;
   - Wide rangeability—It offers a very high turn down ratio;
   - Low pressure loss. It offers much less pressure loss compared to other options;
   - *High reliability:* Not eroded by dirty matters in fluid. Less maintenance required;
   - *Much better performance:* It offers high accuracy;
   - Lower overall cost of ownership.
2. **Disadvantages of V-cones include:**
   - There is no standard available hence no proper field data;
   - Pressure loss is higher in a V-cone when compared with a Venturi;
   - Horizontal installation is preferred, other installations need special attention.

8.1.4 DESIGN DETAILS

There are a number of design features worth noting. These are discussed in brief here.

1. **Flow conditioning:** The geometric construction actually acts as flow conditioning. This design flexibility helps in installation by reducing the straight length requirement. The shape also helps with accurate measurement of disturbed or swirling flows [24].

The V-cone forms very short vortices, passing the cone. These create a low-amplitude, high-frequency signal, which helps in attaining high signal stability. Also, on account of its smooth shape, it can withstand abrasive, dirty, and particle-laden flow without much wear. This helps by reducing the maintenance requirement. The "swept through" design of the cone does not allow for areas of stagnation to accumulate debris, condensation, or particles from the fluid [24].

2. **Improved performance:** Under various flow conditions, a V-cone flow meter offers very high accuracy (in some case as high as 0.5% AR). Also it supports wide rangeability offering turn down as 10:1.
3. **Permanent pressure loss:** Permanent pressure loss is quite low, only being higher than a Venturi when compared with various head type flow meters. In this regard, Fig. I/3.1.1-9 may be referenced for PPL comparison.
4. **Flexibility:** V-cone meters are available in sizes from as small as <25 to 3000 mm. A variety of materials are used for manufacturing. Also the design allows to have painting and jacketing.
5. **Type:** There are two kinds of V-cone; these are the precision tube V-cone and the wafer-cone.

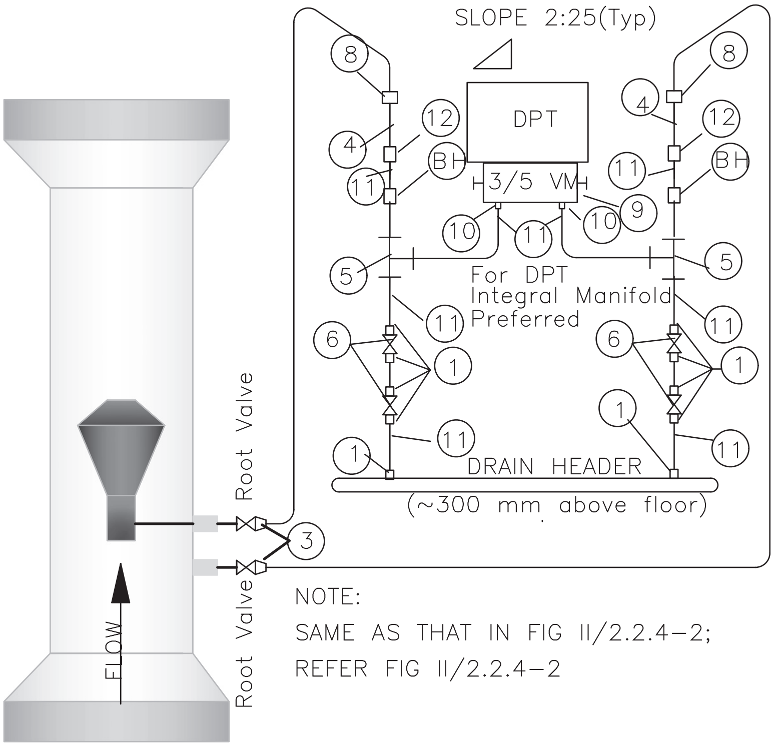
8.1.5 MOUNTING AND INSTALLATION

Short discussions are now given on mounting of the meter assembly and impulse line installation including the requirements for straight length. These discussions will also cover the requirements of various accessories normally used with the meter assembly.

1. **Mounting of the V-cone assembly:** Normally, V-cone assembly is mounted in the pipe with the help of a flange of the required rating as suitable for the particular application. Beveled threaded plains are also available. Normally flanges of different standards, such as ANSI, DIN, JIS, etc. and of different rating, such as 150, 600 lb classes, are available. These flanges could be slip on or weld neck. For piping work the face-to-face dimension of the meter assembly is important and available from the manufacturer's data sheet. This dimensions will be different for wafer type and precision tubes and V-cones.
2. **Tap location and size:** The upstream tapping is normally placed 50 mm upstream of the V-cone (downstream) tapping. Pressure tap size should not be less than 6 mm. Normally 10−25 mm is used.
3. **Impulse line installation:** As indicated in the case of other head type flow elements like orifice/nozzle/Venturi, immediately after the tapping there should be a root valve. For orientation of tapping, guidance as indicated in Fig. II/2.2.2-1 may be used. The isolation valve, valve manifold, etc. should be of the proper rating with packing suitable for the particular application (especially for corrosive/dangerous fluids) [24]. Pressure tappings are part of the flow element assembly. Often, for increased sensitivity and/or for corrosive applications, diaphragms of 75/100 mm diameter are used as a remote seal. In such cases secondary instruments are connected by oil-filled lines/capillaries. It is always recommended that in order to avoid differences in temperature in the two legs of the transmitter, the two impulse lines should be routed in very close proximity (possibly fastened together) so that both are subject to the same temperature (and temperature changes). As in all cases here it is recommended that for gas/steam, an upward impulse line should be used, and for liquids it should be taken down as gas/steam tends to move upward and liquid falls. If this is not possible, installation should be done in the correct way; e.g., for gas applications, impulse lines should be taken up first with a suitable slope, and then taken down (suitable slope) if a secondary instrument is to be installed below the source point. This is stated here but is applicable to all flow elements discussed. Normally V-cones are mounted in a horizontal pipe, but they can be mounted in

vertical pipes also. A typical vertical mounting with secondary instruments above the source point for gas application is shown in Fig. II/8.1.5-1. For steam applications a condensate pot should be used, especially for cases when the source point is below the secondary instrument.

For other typical impulse line installations Figs. II/2.2.4-1 and II/2.2.4-2 or Figs. II/3.2.4-1 and II/3.2.4-2 may be referred to.



DRAWING IS NOT TO SCALE

BILL OF MATERIALS

ITEM NO.	ITEM DESCRIPTION
1	SOCKET WELD TUBE CONNECTOR OF SUITABLE SIZE TO MATCH TUBE SIZES. & CONNECTORS.
2	NOT USED
3	3/4" X 1/2" SW REDUCER
4	3/4 / (1/2) " IMPULSE PIPE SCH:40/80/160(Material to suit the application)
5	1/2"/3/4" EQ.TEE for Tube (Inside Enclosure) OR 1/2"/3/4" SW EQ.TEEforPipe(Outside enclosure)
6	3/4"/ (1/2)" Socket Weld GLOBE VALVE
7	NOT USED
8	1/2" / 3/4" PIPE UNION
9	3 OR 5 VALVE MANIFOLD OF SUITABLE MATERIAL (FORGED For Material see CH XII Sec. 2.0)
10	SUITABLE ADAPTER FOR Valve Manifold for tube connection e.g. Male Connector)
11	1/2"/3/4" SS TUBE
12	1/2" / 3/4" PIPE X TUBE UNION

FIGURE II/8.1.5-1 Impulse line installation for V-cone.

Often the flow element assembly is supplied with an integral valve manifold, secondary instruments, and a DPT. For temperature and pressure compensation, separate temperature tappings are used. However, for static pressure, a parallel connection from the upstream tapping may be used.

4. **Straight length requirement:** Upstream typically 3D, and downstream 1D, where D is the pipe ID. In fact, in cases of single or double 90°bends, etc., the upstream requirement is practically 0. For an expander/butterfly valve etc. around 2–3D straight length would suffice and 1D for downstream.

8.1.6 SPECIFICATION

A short specification of the V-cone is presented in Table II/8.1.7-1. However, in order to complete the specification, depending on applicability, points 2–5 and 18 of Table II/3.5.0-1 and points 22 and 23 of Table II/4.5.0-1 should also be included in the data sheet.

8.1.7 SPECIFIC DATA

For specific data Table II/8.1.7-1 may be referenced.

We now explore another special type head type flow element, the elbow meter.

TABLE II/8.1.7-1 Specification for Annubar (Ref: Section 8.1.6 for complete data)

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Size (precision pipe/wafer)	15–3000 mm/150 mm		
2	Process connections	RF flange slip on, weld neck		
		Material as per application standard: ANSI, BS, JIS, and DIN rating normal 150/300/600/900 lb		
3	Body materials	CS A106; SS316/361l/304; Hastalloy C276; Chrome moly P11/22; inconel 625,		
4	Instrument connection	½″ NPT/BSP or socket weld, 2″or 3″ flange for remote seal		
5	Transmitter mounting	Integral/remote mounting with/without 3- or 5-valve manifold		
6	Process fluids	Liquid, gas, steam		
7	Operating conditions	Max pressure 10 Mpa; rating 900 lb max. Temperature: <800°C		
8	Fittings and accessories	Isolating ball or gate valve, integral 3/5-valve manifold, secondary and tertiary instruments		
9	Flow calibration	Yes for factor K Instrument constant		
10	NDE testing	Standard as applicable		
11	Certification	Material test certificate and other calibration certificate with traceability		
12	Performance	Accuracy ±0.5% to ±1%		
		Repeatability ±0.1%		
		Turndown; 10:1		
		Reynolds number better >8000		

8.2.0 Elbow Tapping Flow Element

The majority of piping configurations already contain elbows, and these can be used for flow measurement. In such cases there will be no additional pressure drop in the line, and there are also no expenses involved for the flow element. A short discussion on elbow tapping flow elements follows.

8.2.1 CHARACTERISTIC FEATURES OF ELBOW TAPPING FLOW ELEMENTS

Elbow tapping flow elements are not really flow elements, rather they are produced in situ from an existing bend. As shown in Fig. II/8.2.1-1 these are formed by two tappings drilled at an angle of, e.g., 45 degrees through the bend. In Fig. II/8.2.1-1 a short radius elbow tapping is shown but it could equally be a long radius bend. Tapping can also be at an angle 22.5 degrees. There is a pair of tappings, one at the outer edge and another at the inner edge. Outer tappings will have higher radius, lower velocity, and higher pressure, while inner tappings will have lower radius, higher velocity, and lower pressure.

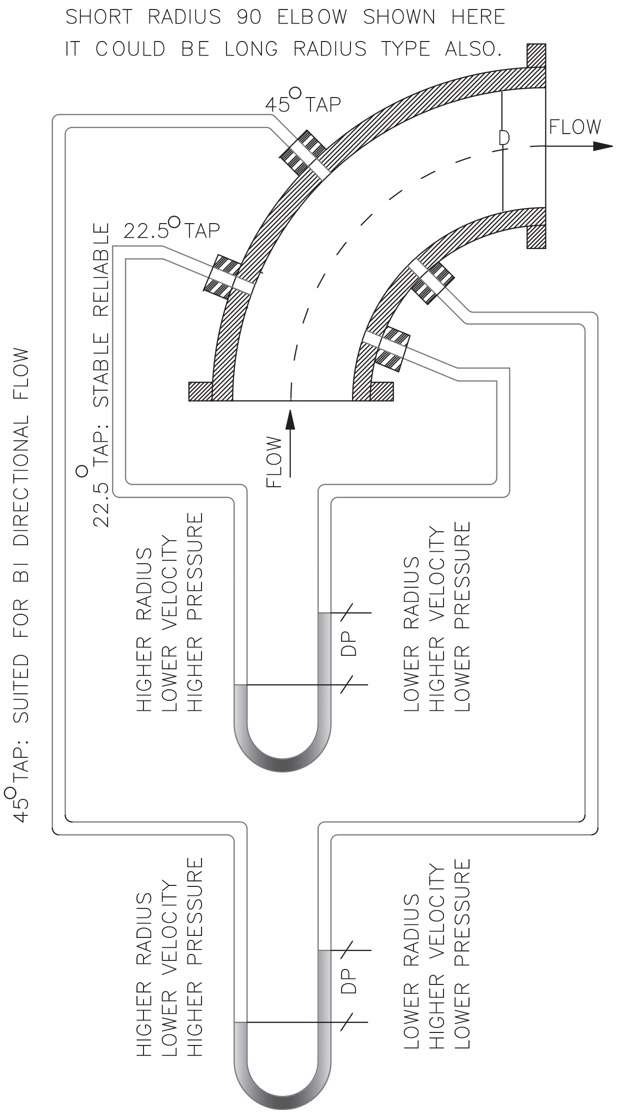


FIGURE II/8.2.1-1 Elbow tap flow element.

The salient features are listed here:

1. Tappings at 45 degrees are more suited to bidirectional flow measurement, while at 22.5 degrees they can provide better stability and reliability.
2. **The major reasons behind unpredictable flow rates include but are not limited to the following:**
   - Turbulence generated due to axial flow [5];
   - Changing difference in velocities between the inner and outer radius of flow; hence force in outer radius;
   - Roughness of the pipe;
   - Relationship between the elbow diameter and pipe diameter.
3. On account of the difference in pressure there may be an accumulation of dirt in DP tappings, in which case purging should be attempted.
4. As the measurement is based on the difference in velocity between two radii and DP generated is low, it is not suitable for flow with lower velocities.
5. As shown in Fig. II/8.2.1-1, the tappings should be perpendicular to the surface.
6. Since the available DP is low, any interference will affect the flow measurement. The straight length requirement for acceptable flow measurement is quite high, at 25D and 10D for upstream and downstream, respectively, where D stands for pipe ID.
7. As stated earlier there is a relationship between pipe ID and that for the elbow. If the elbow diameter is lower than the pipe diameter then on account of higher velocity better results are obtainable.

8. Accuracy should be in the range of 5%−10%, and so is suitable for flow where accuracy is not a factor but PPL is important.
9. It is better to select an existing elbow which is located between two horizontal pipe sections to ensure that the pressure taps are horizontal, and material will not accumulate in them [1].
10. Tappings for an elbow should not exceed 0.125D.
11. The process connection may be welded/ flanged.
12. Instrument connections shall be screwed or flange.

Elbow meters find their applications in the measurement of slurry flow, especially in dredging operations. With this, the discussions on special head type flow elements and head type flow elements are concluded. Since the ***wedge meter*** is very much in use for slurry applications it has been covered in chapter VII (section 5.0.0) where slurry flow measurements have been discussed. A discussion of the variable area meter concludes this chapter.

9.0.0 VARIABLE AREA FLOW METERING

Although Rotameters do not fall under head type metering, yet in this section short discussions are put forward for variable flow metering with the discussion starting with the Rotameter. Apart from the rotameter there are a few other devices such as the valve meter and tapered plug which are also covered.

9.1.0 Rotameter

The rotameter is a variable area meter, used to measure flow with the linear relationship between the flow and displacement of the float. Rotameters in operation are discussed in Subsection 3.1.1.10 in Chapter I. As a continuation of the same this discussion starts with the basic principles of operation.

9.1.1 BASIC PRINCIPLES OF OPERATION OF A ROTAMETER

The variable-area flow meter is a kind head type flow sensor because its functioning depends on the pressure across it. In a conventional head type device the orifice is fixed and variation in the pressure drop across it is measured to compute the flow. In rotameters the pressure drop is kept relatively constant, and the orifice area varies for flow measurement. As the area is varied for flow measurement the rotameter is also referred to as a variable flow meter. Therefore, this variable area flow meter (rotameter) consists of a tapered upright measuring tube with a variable area, i.e., starting with a narrow tube at the bottom, it ends up in a wider opening. Naturally, the flow has to be in a vertical plane from the bottom to the top. In the tube there is one specially shaped float which moves up and down based on amount of flow increase and decrease. Based on flow from the bottom to top, the float rises until there is an annular gap between the tube wall and the float, i.e., when the equilibrium of forces acting on the float is reached. With reference to Fig. II/9.1.1-1A, it can be seen that there are three forces acting on the float.

These forces are:

- *Upward force:* The flow force; which changes with flow until equilibrium is reached. With a change in inlet pressure, the flow force also changes.
- *Upward force:* The buoyancy force, which is in line with Archimedes principle, depends on the volume of the float (i.e., the volume of the fluid displaced by the float) and the density of the fluid medium. It is constant unless the fluid is changed or the float is changed.
- *Downward force due to gravity:* The weight of the float which is dependent on the mass of the float. Based on the application the flow can be manufactured from stainless steel, aluminum, or hard rubber to name a few materials normally used.

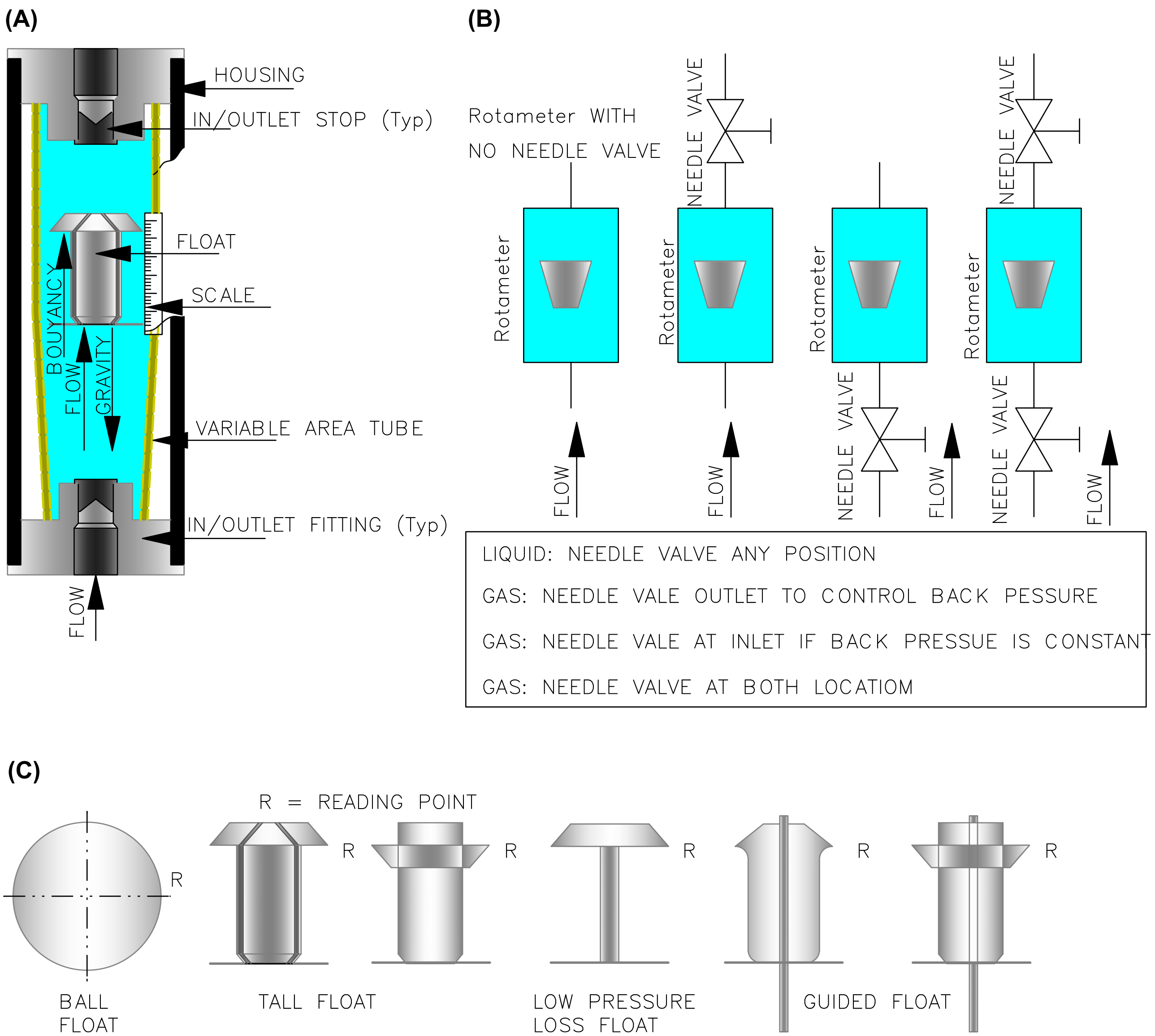


FIGURE II/9.1.1-1 Rotameter details. (A) Rotameter front view. (B) Rotameter and needle valve. (C) Rotameter float types.

When the inlet pressure/flow force decreases, due to gravity the float drops to obtain a new equilibrium position. Similarly, an increase in flow forces the float up until its resistance to the fluid flow is balanced by the float's *buoyed weight* in the fluid, a value which is constant and independent of the flow rate [25]. The flow rate values can be read on a scale. Corresponding to each flow there will be a defined annular gap resulting from the conical form of the measuring tube and the specific float position. A scale is engraved on the glass conical tube or there is a scale pointer in a metallic conical tube. In the case of a metallic tube a magnet may be attached to the float and a pointer is magnetically coupled with the pointer. There are rotameters with transmission facilities. In such cases, for example, there *may* be a rod made of soft iron attached to the float. This, in conjunction with the linear variable differential transformer (LVDT), can produce an electrical signal. Output of the LVDT may be used for a 4—20 mADC transmission signal.

9.1.2 ROTAMETER FLOW SIZING

The tapered tube's gradually increasing diameter provides a related increase in the annular area around the float, and is designed in accordance with the basic equation for volumetric flow rate:

$$q = K \cdot A \cdot \sqrt{gh} \qquad \text{(II/9.1.1-1)}$$

where q = volumetric flow rate; **K** = a constant; A = annular area between the float and the tube wall; g = force of gravity; and h = pressure drop (head) across the float (hence also related to the density of the fluid). As stated earlier, "h" head loss across the float is kept relatively constant and the annular area is varied. Generally, head loss is kept constant over an operating range 10:1, so linearity is true for this operating range. Also, a drop across the rotameter is quite low at around 6.89 KPa [1]. For low pressure drop applications, a special low-pressure float in conjunction with a bead guided tube are used. This means that, in a variable area flow meter the annular area "A" needs to be varied with variations in the flow rate. Therefore, during design, a tube taper area is determined so that the height of the float in the tube gives a measurement of the flow rate. The float is very important in rotameters. The reading of a rotameter is dependent on the nature of the fluid being metered. Normally rotameters are calibrated with calibration data for air and water. Therefore, it is necessary to determine the water equivalent and air equivalent for the fluid and float combination. If q is metered volume then for liquid applications:

$$\text{Water equivalent volume} = q \cdot \{(\rho_f - \rho_2) \cdot \rho_1 / (\rho_f - \rho_1) \cdot \rho_2\}^{1/2} \qquad \text{(II/9.1.1-2)}$$

where ρ_f = density of float; ρ_1 = density of calibration liquid (water = 1); and ρ_2 = density of fluid under reference.

$$\text{Water equivalent mass} = q \cdot \{(\rho_f - \rho_2) \cdot \rho_2 / (\rho_f - \rho_1) \cdot \rho_1\}^{1/2} \qquad \text{(II/9.1.1-3)}$$

For gases similar calculations are also possible. However, in practice manufacturers provide a table(s) as a means to correct the values listed for various gases whose operating conditions deviate from the normal conditions (NTP) used during calibration. If the meter is calibrated in terms of air in NTP and it is to be used for another gas at different operating conditions then it is corrected for density correction from the table **and** correction factors for changes in operating conditions. These correction factors for operating conditions are given in Table II/9.1.1-1 [25] where K_p = correction factor for pressure; K_t = correction factor for temperature; p_1 = (1.013 + calibration pressure) in bar; p_2 = (1.013 + new operating pressure) in bar; t_1 = 273K + calibration temperature in °C; and t_2 = 273 K + new calibration temperature in °C.

The above calculation does not take into account the viscosity effect. Normally, floats are designed for operation independent of wide viscosity range, i.e., within these ranges the viscosity of the fluid can vary without affecting the flow rate measurements. There is a term, viscosity immunity ceiling, listed in the manufacturer's catalog in the flow range tables for these variable area flow meters. If the VIC value calculated for the application is less than or exactly equal to the VIC value listed in the flow range tables, there is no viscosity effect on the measurements. If the VIC number is higher than the value listed, then the scale for the flow meter must be created for specific fluid viscosity at the factory [25].

TABLE II/9.1.1-1 Rotameter Operating Condition Correction Factor

Corrections for Parameter	Normal/ Weight	Actual Flow
Pressure	$K_p = \sqrt{p_2/p_1}$	$K_p = \sqrt{p_1/p_2}$
Temperature	$K_t = \sqrt{t_1/t_2}$	$K_t = \sqrt{t_2/t_1}$

Variable Area Flow meter; Basic Fundamentals and Descriptions; Technical Specifications, D184B003U46, Rev: 01, ABB Limited. https://library.e.abb.com/public/c125698f006840e9c1256a7f003f7ae1/D184B003U46.pdf. Courtesy: ABB.

All major manufacturers (namely, ABB, Kronhe, Omega, etc.), offer the necessary software (with different names), by which it is possible to select the rotameter for a particular application and to size the meter. The latest version of VDI/VDE 3513 part I provides guidelines for sizing calculations.

9.1.3 ROTAMETER FEATURES AND APPLICATIONS

1. **Features:** The major features of rotameters include but are not limited to:
   - Economic, reliable, easy-to-read displays;
   - Linear fail-safe flow indication (Q ∞ A; keeping pressure drop constant);
   - Transmission and flow control possible;
   - With an integral needle valve it is possible to take care of pressure variations;
   - Easy field replacement possible;
   - Materials and designs to suit application needs;
   - Rotameter is self-cleaning; as it goes up due to velocity it removes foreign materials;
   - Rotameter is least affected by piping configuration;
   - Useable for direct flow measurement as well as an accessory for other measurements;
   - Flow measurements are done only in a vertical line with the flow inlet and outlets at the bottom and top, respectively.
2. **Applications:** Rotameters have a wide range of applications in instrumentation engineering, the major application areas are:
   - Direct flow measurement for liquid or gas e.g. oxygen supply to patient;
   - Process analysis system for sample flow rate, e.g., steam and water analysis system in power plant;
   - Rotating equipment flow measurement;
   - High-pressure flow on offshore oil platforms;
   - Chemical dosing and injection systems;
   - Bypass or indirect flow measurement with restriction orifice;
   - Purge liquid or gas metering;
   - Purge method of process parameter measurement (for example, pressure or DP/level measurement).

9.1.4 ROTAMETER TYPES

Rotameters can be classified on the basis of their construction, such as glass rotameters and metal tube rotameters. Also, Rotameters can be classified on the basis of their functions, such as direct rotameters or bypass rotameters. Rotameters can also be classified by their use, such as for local indications or a rotameter with transmission facility, etc.

1. **Constructional classification:** Glass rotameters and metal tube rotameters are the two main basic types of rotameter from a construction point of view. When the basic purpose is for indication only and to be used for low-pressure applications, then glass rotameters are the better choice. When the application demands higher pressure or temperature and/or the fluid is not suitable for glass then metal tube rotameters are deployed. In the case of a glass tube rotameter, the scale may be directly on the glass tube and in the case of a metal tube rotameter there may be other means for scale indication attached to the main body. Some also use a dial type indication.
2. **Functional classification:** Rotameters can also be classified from a functional point of view. One type is only for local indications by scale pointer types. Scales may be on a vertical scale or a dial type indication with the help of mechanical coupling/magnetic coupling. However, both are meant for local indications. There may, however, be another version with transmission facility. In such cases the float movement is magnetically coupled to the electrical circuit for long-distance transmission in 4−20 mADC.
3. **Application classification:** As stated earlier, rotameters can be deployed for direct flow reading. However, such an application has some limitations for large pipe flow measurement

or if the pipe is not laid vertically. In such cases, bypass rotameters are deployed as shown in Fig. II/9.1.4-1A. In such cases in the main line orifice plates are used to divert a proportionate flow through the bypass line which is then measured to compute the flow in the main line. Usually there will be a range orifice to decide the flow rangeability. The other type is a purge rotameter as shown in Fig. II/9.1.4-1B. These are deployed for measurement of pressure, differential pressure, and level measurements where it is difficult to use a standard metering device for corrosion/choking, etc. Measurement of mill DP in a power plant is an example of this. Normally air is sent to the measuring point at slightly greater pressure than the measuring

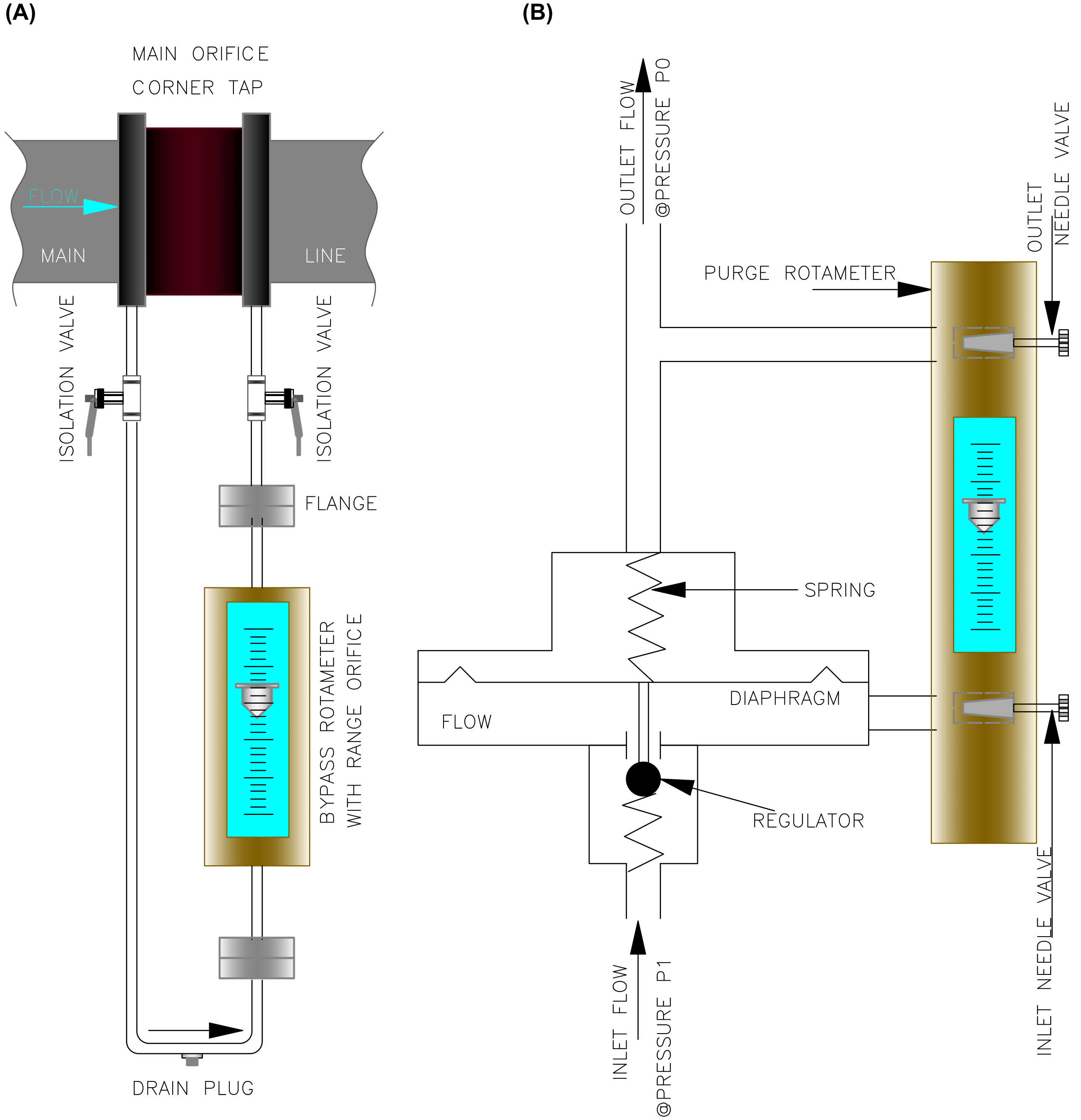


FIGURE II/9.1.4-1 Bypass and purge rotameter. (A) Bypass rotameter. (B) Purge rotameter.

point pressure applied. Such excess air pressure is maintained by the DP regulator shown. A constant-flow DP regulator is used to maintain the purge flow rate at a desired level. In such a case, during commissioning, slightly higher air pressure is ensured by the very small amount of air flow in the line. Such air flow is ensured by the rotameter. Here the functions of needle valves are important. The location of the needle valve(s) with respect to the rotameter, are dealt with later.

9.1.5 ROTAMETER DESIGN DETAILS

A rotameter consists of major components: meter tube, float, and end fittings. These are discussed briefly here.

1. **Meter tube:** Based on operating conditions, there are two types of meter tubes. Meter tubes can be made of glass, metal, or plastic.
   - Glass meter tubes made of borosilicate glass are typically used for simple but reliable indications of flow rate with a high level of reliability. These are suitable for metering process media with temperatures less than 200°C and pressures up to about 2–3 MPa. Linear scale graduations can be an arbitrary 0–100% of the meter range. Protection of the glass tube from thermal and mechanical shocks and accidental leakage/spillages is necessary. Therefore, glass meter tubes are often installed in a metal frame with a clear thick front shield. Calibration can be direct reading in terms of a specific gas or liquid, or by using a correction factor in graphical form. There are several types of glass tubes such as:
     - Tri flat tube for small sizes;
     - Plain taper meter tube;
     - Bead guided meter tube.
   - *Metal meter tube:* There are applications where glass is not suitable, e.g., operating conditions are too high, such as temperatures over 400°C and pressure as high as 70 MPa or where there is a possibility of water hammering. These are usually manufactured from stainless steel. In these cases the float positions are determined indirectly, e.g., by a float follower and/or by either magnetic (use of permanent magnet) or electrical techniques. Armored rotameters can be used for corrosive fluids and steam applications.
   - *Plastic meter tube:* In many applications plastic tubes are also used (preferable from a cost point of view). These are normally constructed of polycarbonate, acrylic, polysulfone, or other plastic flow meters. Apart from the cost point of view, these are used in cases where metal wetted parts cannot be tolerated, e.g., deionized water. For highly corrosive applications, PTFE flow meters are available. These are available with translucent PFA metering tubes. These meters are designed with PTFE seals and O-rings, excluding elastomeric materials [1].
2. **Float:** Floats are available in a variety of materials. The material selection is guided by the fluid medium to be measured, the materials include: stainless steel, titanium, aluminum, Monel, nickel, Hastelloy C, glass, synthetic sapphire, PVC, hard rubber, Teflon, and polypropylene. Centering of the float is important, this is usually done by:
   - Slot in float head;
   - Three molded ribs in metering cone;
   - Fixed center guide.

   There are various shapes of floats. The viscosity of the fluid directly affects the selection of float type and shape. Various types and shapes of float are depicted in Fig. II/9.1.1-1C. Table II/9.1.5-1 lists various types of floats with their uses (Fig. II/9.1.1-1C).
3. **Scales:** There are various scales available, these are:
   - *Direct reading scale:* Volume/mass flow per unit time;
   - *Percentage scale:* Linearized percentage standard scale;
   - *Millimeter scale:* Usually for fixed flow rate;

TABLE II/9.1.5-1 Float Types and Usage

Float Type	Usage	Remarks
Ball float	Used for smaller flow rate	1/16″ to 3/8″ size
	The shape is not changed hence coefficient is clearly defined and not linear with change in viscosity	
Float with tail guides	These are used for bead-guided tubes. The float is guided by the metering edge and the tail guide at the three ribs in the bead guide meter tube [25]	Not suitable for high-viscosity fluids
Low-pressure drop float	Used for the cases where very low-pressure drop is desired	
Pole-guided float	These are used with plain tapered meter tubes with a hole through the meter tube axis and are guided by a pole positioned in the meter tube	
Tapered float	These are used in cylindrical tube with orifice. Guided rod—a part of float moving in a guide element attached to the metering tube	

- *Diameter ratio scale:* Linearized ratio scale which indicates diameter ratio of the effective internal meter tube diameter (Dt) and the float diameter (Df) [25].

4. **Accuracy:** VDI/VDE 3513 part 2 provides the guidelines for defining the permissible error. According to VDE 3513-2:2008 the measurement error can be due to:
   - Inaccurate determination of the scale by miscalculation;
   - Inaccurate execution or mounting of the scale or change due to subsequent influences;
   - Restoring force for pointer (float) is constant throughout the range;
   - Characteristic curve of variable area meters are nonlinear, broadening toward the lower end.

     Earlier accuracy class definitions have been modified in the VDE standard. Linearity and accuracy are now linked.
   - *Linearity limit:* The ***linearity limit*** is the flow limit value in % of the full scale. Above this limit, the permissible, relative error is constant, and below this limit the permissible error increases towards lower flow rates.
   - *Permissible error:* Constant, permissible error in % of measured value, applicable above the linearity limit of the instrument. This means that if the error limit is stated as 1% that refers to a constant, permissible measuring error of 1% of the current measured value.
5. **Needle valve and rotameter:** Selection and installation details of variable flow meters are available in the latest version of VDI/VDE 3513 part 3. Here a short discussion has been put forward for placement of the needle valve which is quite often used with rotameters. In connection with this Fig. II/9.1.1-1B may be referenced. When a rotameter is used for liquid application the location of the needle valve is not as important as it is for gas measurement in which density varies as per changes in pressure. Generally, needle valves are put in the outlet side to ensure that the back pressure is not varied so that there is no change in the pressure condition of the fluid. If it is ensured that the back pressure is constant

then the needle valve can be located at the inlet. For measurement of atmospheric pressure the needle valve will be at the inlet. For a purge rotameter the needle valve may be at the inlet to set the flow as there is a DP regulator to control the back pressure. Therefore, in Fig. II/9.1.4-1B it may be kept at the fixed opening.

We now concentrate on the specifications for a rotameter.

9.1.6 ROTAMETER SPECIFICATIONS

1. **General:** A short specification pertinent to rotameters has been elaborated in Table II/9.1.6-1. However, in order to complete the specification, depending on applicability, points 2−5 and 18 of Table II/3.5.0-1 and point 23 of Table II/4.5.0-1 should also be included in the data sheet.
2. **Specific data:** For specific data, Table II/9.1.6-1 may be referenced.

9.2.0 Other Variable Area Flow Meters

There are a few other types of variable area flow meters. One is the piston-type flow meter, where there is a fixed tapered cone type plug. The piston is held in place at the base of the cone (in the "no flow position"), with the help of a duly calibrated spring. When flow starts, it moves the piston against the spring, creating an annular orifice formed by a piston and tapered cone. The piston movement and orifice area are proportional to the flow rate. Such meters can offer an accuracy of

TABLE II/9.1.6-1 Specification for a Rotameter (Ref: Section 9.1.6.1 for complete data)

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Application	Direct/bypass/purge		Purpose to be defined
2	Meter tube type	Glass/metal/plastic		
3	Meter tube DIa/ length taper ratio	1/2/3/4″dia 75/150/250 mm*		*Typical data depend on application
4	Scale type and size	Linear/angular; 75/150 mm or 180(say) angular)		
5	Face-to-face dimension	Screwed/flange/flange plate with screwed connections		
6	Meter tube material	Borosilicate glass/SS 304/316/316L, Hastalloy C titanium, etc.		
7	Float materials	SS 316/316L, PTFE, PVC, aluminum, Hastalloy C, titanium		
8	End fittings	Polypropylene, SS 304/316/316L, Hastalloy C, titanium		
9	IP class	IP67		
10	Facility	Transmission/control		
11	Set point	% full scale		
12	Contact rating	3 A @ 240 VAC or 0.3 A @220 VDC		
13	Explosion proof	Yes/no if yes protection class		
14	Accuracy	Error <1% reading (for example)		

5%−8% FSD. In some cases in place of a calibrated spring, force of gravity can be utilized to bring the piston to the base position in no-flow condition. However, in such cases the flow meter needs to be in a vertical line. However, in the case of a spring-loaded one it can be in a horizontal line also. There are units which are vane operated, in such case fluid flow forces the vane to rotate against a spring, increasing the orifice area for flow. The piston position gives the flow rate read against a scale like in a rotameter. These spring-operated tapered plug meters can be used in operating conditions like flow: 400 L/min; pressure: 7 bar; and temperature: 200°C. These meters are used in high-pressure oil applications and are available in sizes up to 150 mm.

There are other flow meters which operate by a flowing stream lifting hinged gates or forcing spring-loaded vanes to open. The variable gate is a mix of a variable area and flume type flow meter, used to measure wastewater or other liquids in open channels or in partially filled pipes [1].

The discussion on head type flow measurement and also on variable area flow metering is now complete, so that the reader can now look out for velocity- and force-based flow meters.

LIST OF ABBREVIATIONS

ABS Absolute
AR Actual reading (in connection with accuracy)
CHU Constant head unit
DP Differential pressure
DPT Differential pressure transmitter/transducer
FSD Full-scale division (in connection with accuracy)
HVAC Heating ventilation and air conditioning
ID Internal diameter
LHS Left-hand side
LIE Local instrument enclosure
LVDT Linear variable differential transformer
NB Nominal bore
OD Outer diameter
PPL Permanent pressure loss
RF Raised face or radio frequency
RHS Right-hand side
RTJ Ring tongue joint
RTD Resistance temperature detector
SS Stainless steel
VIC Viscosity immunity ceiling
VM Valve manifold
WRT With respect to

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CHAPTER III

OPEN-CHANNEL FLOW MEASUREMENT

Chapter Outline

1.0.0 BASIC PRINCIPLES AND GENERAL DISCUSSION

Everyone is well aware of the flow of fluids in an open channel. Water flow in a river is an example of natural open-channel flow. In contrast, water flow in an irrigation channel is artificial open-channel flow. Sewerage, raw/intake water flow for power plants, water treatment plants, pulp and paper plants, petrochemical, metallurgical, and many other industrial plants use large amounts of water as part of their operations in open channels. The measurement of such flow is essential. Open channel flows are not entirely covered by rigid boundaries; part of the flow is in contract with empty space/atmosphere. On account of the flow surface being freely deformable, it is called the free surface. Frankly speaking, flows of liquid at the Earth's surface, i.e., the ocean, or rivers, are not open-channel flows, in the sense that they are in contact with another fluid—the atmosphere; and hence this is a two-phase medium. However, the large difference in density between water and air present in overlying atmosphere is ignored for all practical purposes. All of the principles and techniques for dealing with velocity, boundary resistance, etc., developed in Chapter I for closed conduits also hold for open-channel flows. Additionally, open-channel flows involve important issues of complexity beyond what we have covered in closed conduits; namely, on account of the free surface, the geometry of the flow can also change in the flow direction because of the behavior of the flow itself. Therefore, acceleration due to gravity plays a major role because the force of gravity helps to shape the free surface.

The flow measurement proposition is not always very simple, especially when there are many variables associated with these flow channels. However, it is not as difficult as it sounds because in the majority of cases it is possible to express most of these variable features in terms of a few variables in a simplified theory utilizing the continuity and energy equations of fluid

Plant Flow Measurement and Control Handbook. https://doi.org/10.1016/B978-0-12-812437-6.00003-2

mechanics. Like flow in closed conduits, the major driving forces here are also those of inertia, gravity, and viscosity, etc. However, there is a fundamental difference between closed conduit flow and open channel flow. In the case of an open channel there will be free surface that is subject to atmospheric pressure, while for a closed conduit there will not be any free surface but it is subject to hydraulic pressure inside the pipe. There are a number of basic logical assumptions for open-channel flow measurement and flow computations. These basic assumptions include:

- Flow is turbulent, as the depths and dimensions are greater than the boundary layer thickness.
- Considering that turbulent flow and channel length are much larger than the cross-section, a single average velocity measurement will be sufficient for calculations.
- On account of other large sizes, capillary forces are negligible.

The above assumptions are helpful in deriving various mathematical expressions for flow computations and flow element sizing discussed later in this section. However, before that it is better to look into the fundamentals of the approach to open-channel flow measurement.

1.0.1 APPROACHES FOR OPEN CHANNEL FLOW MEASUREMENT

In this section a few important terms, which may be used during detailed discussion, will be discussed (as a part of recapitulation). In an open channel, the flow area is in contact with the air, i.e., it is subject to atmospheric pressure. As in an open channel there is no force, i.e., pressure (like that in a closed conduit), at one end to make the flow to happen, the flow rate depends on the gradient of the slope of the channel and friction along the walls. For uniform flow, there will be a progressive drop in the level from the source to the end. Thus, in an open channel, the total energy is the kinetic energy present in the form of the velocity head for flow, and the pressure energy due to the difference in water depth. This is further elaborated on in Section 1.1.7. Thus,

$$\text{Total energy} = v^2/2g + h \qquad \text{(III/1.0.1-1)}$$

where, v is the flow rate (proportional); g is the gravitational constant; h (also represented as y or d) is the water depth measured from the channel bottom. As stated earlier, there is negligible capillary force. In connection with this, Fig. III/1.0.2-1 may be referred for comparison. From Eq. III/1.0.1-1 it is clear that when there is a change in velocity head there will be also be a change in water depth. When velocity, i.e., flow, increases there will be a decrease in the depth of the water; conversely when there is a decrease in flow, the velocity head will decrease, and there will be an increase in the water depth. In this regard, Table III/1.1.7-1 may be referenced. A drop in water flow area is known as "drawdown." In the case of a closed conduit, changes in pressure result in changes in flow, but the relative level in the conduit does not change. Now, with this concept in mind, a short discussion is presented to establish the basis for open-channel flow measurement. Prior to giving further details a few relevant terms which will be used frequently during subsequent discussions are discussed and defined.

1. **Froude number (Fr):** Like the Reynolds number, the Froude number is also a dimensionless ratio used to describe different flow regimes of open-channel flow. The Froude number is a ratio of the gravitational forces and inertial force which represent wave celerity.

   So, Fr = gravitational force to move the water/wave celerity or inertial force.

$$\text{Or Froude number Fr} = \frac{v}{\sqrt{gH}} \qquad \text{(III/1.0.1-2)}$$

   where v = water velocity; H = hydraulic depth; and g = gravity. Depending on whether the value of Fr is greater than or less than supercritical (Fr > 1) and subcritical unity (Fr < 1), flows are defined. At critical flow Fr = 1. Based on the Froude number a

few terms that are very important for open-channel flow measurement are defined and listed below.

- *Wave celerity:* In an open-channel flow there are small waves in the stream. The speed of a small wave on the water surface relative to the speed of the water is referred to as wave celerity. The velocity at a critical depth is equal to the ***wave celerity***.
- *Critical flow:* At critical flow, flow celerity equals flow velocity. From the above discussions it is clear that this type of flow can happen when there is a strong contraction created by a lift in the bottom and/or a narrowing of the width of the channel, or by a sudden change in the slope of the channel bottom. So, at critical flow, any disturbance to the surface will remain stationary and not be propagated. This happens at water flow depth equal to actual water depth and is the critical depth. Also, the slope at which it occurs is referred to as the critical slope.
- *Subcritical flow:* In subcritical flow ($Fr < 1$), the inertial force is stronger, so the flow is controlled from a downstream point and is transmitted upstream and can lead to backwater effects. In other words, in subcritical flow, velocity is less than wave velocity (and critical velocity), the actual water flow depth is above (lower depth) that for critical flow depth and the associated slope is less than the critical slope and it is in a lower energy state (than that at critical flow).
- *Supercritical flow:* In supercritical flow ($Fr > 1$), the gravitational (or driving) force is stronger, so the flow is controlled from upstream and disturbances are transmitted downstream. In supercritical flow, the actual flow depth is below (higher depth) that for critical flow depth and the associated slope is greater than the critical slope and is in a higher energy state (than that at critical flow). *The discussions presented above can be better explained with specific energy discussed in Section 1.1.7 of this chapter.*

2. **Hydraulic jump:** The hydraulic jump is based on the Froude number—hence the critical for an open-channel flow, is another important physical issue. Hydraulic jump is basically a physical situation involving both supercritical flow and subcritical flow. It is often seen that supercritical flow due to a steep slope is not sustained, and then abruptly changes to subcritical flow in the presence of a hydraulic jump to make the transition possible. As shown in Fig. III/1.0.1-1A, the slope of a channel decreases from a steep slope on which supercritical flow was maintained, suddenly changing to a mild slope to sustain subcritical flow in the presence of a hydraulic jump. Therefore, hydraulic jump occurs wherever a supercritical flow changes to a subcritical flow. The hydraulic jump provides a transition to subcritical from supercritical flow. Therefore, a hydraulic jump is defined as a rise in the level of water in an open channel which can be designed and controlled. So, a hydraulic jump occurs when a liquid with higher velocity discharges into a zone that has a lower velocity. On account of this physical phenomenon, there will be an increase in height because kinetic energy is transformed into potential energy. There will be turbulence, which may cause loss of some energy as heat. To calculate changes in height it is necessary to apply a continuity equation and conservation of momentum (which helps to calculate heat dissipation due to the shock wave).
   - *Classification of hydraulic jumps:* Based on the Froude number, already discussed above, hydraulic jumps are classified as follows (see also the illustrations in Fig. III/1.0.1-1B−F) [1]:
     - Undular jump: Low energy dissipation (Fig. III/1.0.1-1B);
     - Weak jump: Low energy dissipation and smooth downstream water surface (Fig. III/1.0.1-1C);

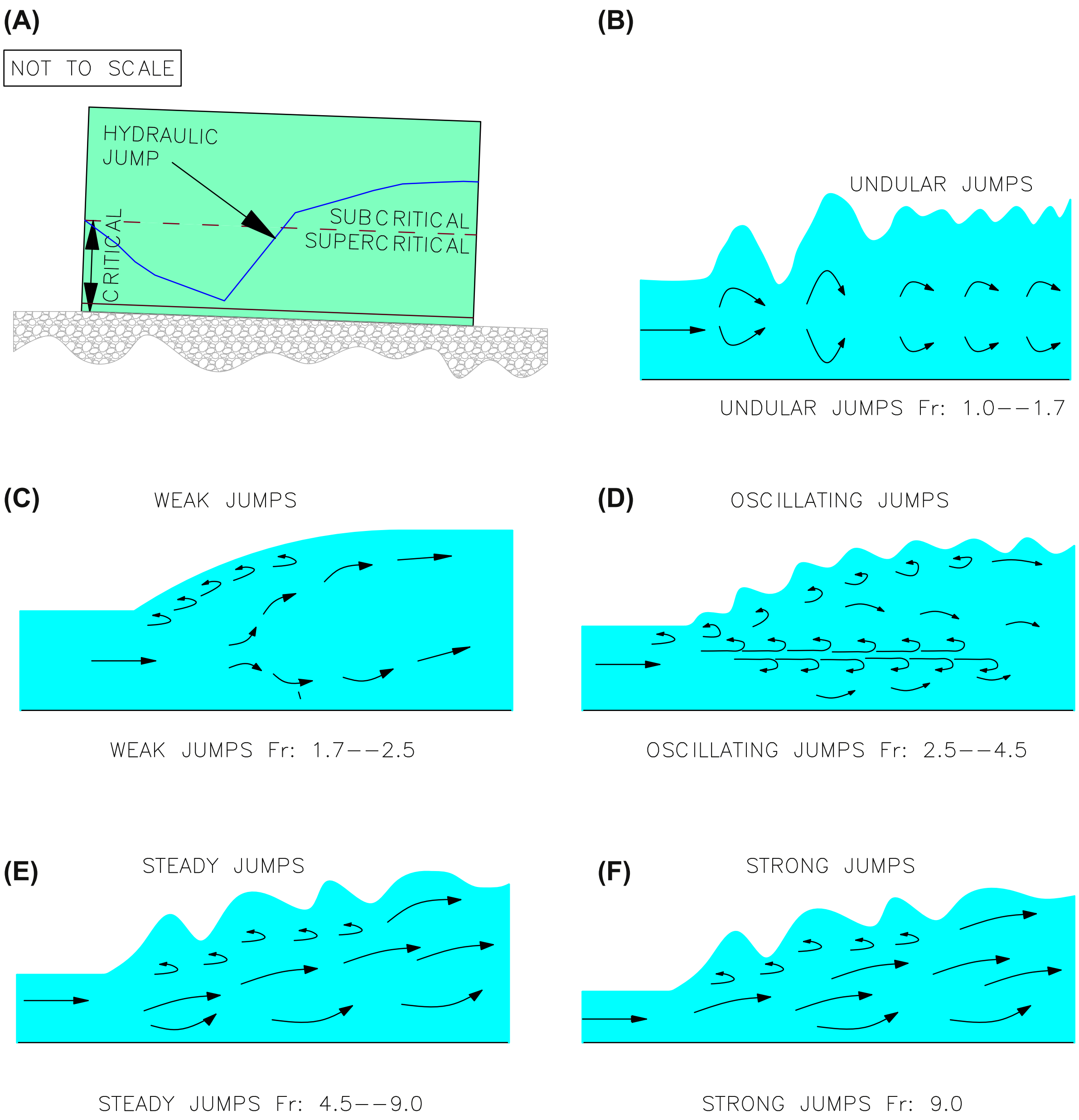


FIGURE III/1.0.1-1 (A) Hydraulic jump definition. (B) Undular hydraulic jump. (C) Weak hydraulic jump. (D) Oscillating hydraulic jump. (E) Steady hydraulic jump. (F) Strong hydraulic jump. *(B) Based on N. Lind, J. McCallum, M.M. Yaqoob, Hydraulic Jumps, CIVE 401 Project.*

- ○ Oscillating jump: Fluctuations and downstream turbulence (Fig. III/1.0.1-1D);
- ○ Steady jump: steady balanced jump at the same location and turbulence is confined within the jump (Fig. III/1.0.1-1E);
- ○ Strong jump: High dissipation and change in depth as shown (Fig. III/1.0.1-1F).

Natural hydraulic jumps in rivers are quite common.

- *Advantages of hydraulic jumps:* Hydraulic jumps offer a number of advantages listed below:
  - ○ Energy dissipation of water over a spillway;
  - ○ High water level in the downstream side;

   - Traps air to increase dissolved oxygen;
   - Prevention of downstream dam structure scouring.
- *Disadvantages of hydraulic jumps:* There are a few disadvantages, these are:
   - Erosion of hydraulic surface and damage of channel bank due to downstream turbulence;
   - Unhealthy for fisheries,
- *Applications:* Hydraulic jumps are applied in dam designs to dissipate energy over a spillway and they are used for fun sports, e.g., rafting.

3. **Relevant important terms:** At the beginning, it is better to get definitions and explanations for a few other relevant terms which will be frequently encountered in subsequent discussions. Some of these relevant important terms with necessary explanations are presented below.
   - *Closed conduit discharge:* Closed conduit discharge is a discharge confined to a closed conduit, when the liquid is confined in a pipe (not in contact with the atmosphere) and subjected to pressure other than atmospheric pressure.
   - *Open conduit discharge:* Open conduit discharge is a discharge is an open channel, when the surface of the water is in contact with the air and is subjected to atmospheric pressure only.
   - *Time-dependent variations:* Time-dependent variations at point give rise to two types: Steady flow and unsteady flow.
   - *Steady flow:* In steady flow at a given point there will be no change in flow depth with time.
   - *Unsteady flow:* In contrast to steady flow, in unsteady flow at a given point there will be a change in flow depth with time.
   - *Space-dependent uniform flow:* Space-dependent variations give rise to uniform flow. When in an open channel, if both *depth and velocity* of flow remain constant at every section of the channel then it is said to be uniform flow and this is possible when there is equilibrium between force due to gravity and resistance force, i.e., total energy is constant (see Eq. III/1.0.1-1). In other words the slope of the water surface is parallel to the slope of the channel bottom as shown in Fig. III/1.0.2-1. So, depth y does not vary with distance x, i.e., $\frac{dy}{dx} = 0$.
   - *Steady uniform flow:* From the above, it follows that for steady uniform flow, depth and velocity of flow do not change with time and space.
   - *Steady nonuniform flow:* In open channel flow measurement, as flow is said to be steady, nonuniform flow means that the depth of flow varies with space (different at different sections, i.e., at different distances) but *not* with time (hence it is steady). Steady nonuniform flow can be of two types, i.e., $\frac{dy}{dx} \neq 0$.
   - *Gradually varied steady nonuniform flow:* In this type, there will be change in energy and frictional resistance, i.e., there will be a moderate acceleration or deceleration of liquid due to a change in the slope of the channel bottom, i.e., $\frac{dy}{dx} \ll 1$.
   - *Rapidly varied steady nonuniform flow:* In this type, there will be a change in energy and momentum. This means that in contrast to the moderate acceleration or deceleration of a liquid, there will be a rapid change due to the sudden change in the slope of the channel bottom. This may give rise to critical flow, i.e., $\frac{dy}{dx} \sim 1$.
   - *Unsteady nonuniform flow:* in this type, there will be changes in the depth of flow with time and space. This is a common type of flow. These require solutions for energy, friction, and momentum equations. However, for practical purposes the flow is sufficiently close to steady nonuniform flow, therefore these can be analyzed with energy and friction equations.
4. **Types of open-channel flow measurements:** There are a number of approaches for open-channel flow measurement. These include:
   - *Hydraulic structure:* The hydraulic structures are often referred to as primary

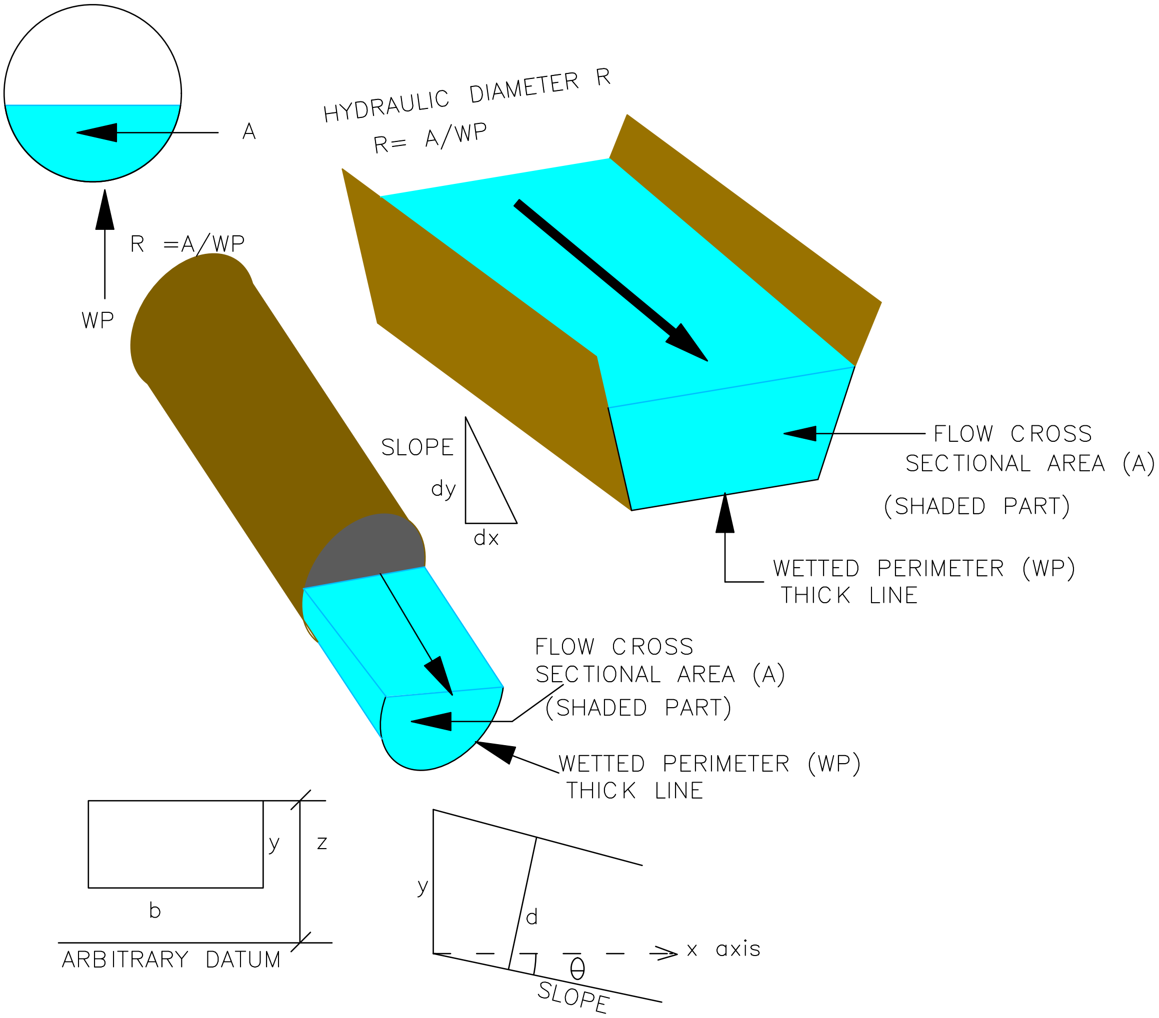
(measuring) devices. Basic information on gravity (causing the flow), the inertial and viscosity forces (that slow it down) are utilized to compute flow. Two hydraulic structures, namely, "weir" or "control flumes" are used to create a critical flow. Then the flow regime variations are exploited to establish the relationship between the force of gravity and the retarding forces such as the inertial and viscosity forces. In the final equation (discussed later) the relationship between depth before the primary device and flow is established. This is the most common method used to determine and compute flow with the help of calculations based solely on water depth upstream from the primary measuring device flow, i.e., by monitoring the level with a secondary level-sensing instrument. Weir and control flumes are discussed at length in subsequent sections. The following are the major issues for primary measuring device selection:

- Maximum and minimum flow rates through the primary device with due considerations for limits to the primary device as designed;
- Fluctuations in water depth, according to minimum and maximum flows;
- Primary device approach conditions and loss of pressure due to inserting the device [2];
- Presence of solid material and possible obstructions;
- Compliant to the relevant standards governing installation;
- Testing and calibration are possible [2].

• *Hydraulic radius and slope:* This is based on the principle of depth and velocity. Here the mechanics of movement of a liquid are considered without examining the underlying forces. Hydraulic radius and slope are the major factors considered. Subsection 1.0.2.5 may be referenced for an explanation of the hydraulic radius and other related terms. The flow is computed by the most commonly used open-channel flow equation—Manning's equation. In this formula the roughness component is assumed to be constant over the full range of flows and is represented by Gaucklar–Manning's roughness coefficient n. The most popular *Manning formula* is as follows:

$$q = \left(K \cdot A \cdot R^{2/3} \cdot S_0^{1/2}\right) \Big/ n \qquad \text{(III/1.0.1-3)}$$

where, q = flow rate; A = flow cross-sectional area; R = hydraulic radius (cross-sectional area divided by wetted perimeter); S_0 = slope of the hydraulic gradient (refer to Eq. III/1.1.6-2); n = roughness coefficient based on channel material and condition; K = constant dependent upon units: In *SI* units it is **1.0** and for *US* units it is **1.49**. The cross-sectional area A and the hydraulic radius R are calculated based on the liquid depth, and the size and shape of the channel. From the actual installation document, the slope S is often estimated. The roughness coefficient n is selected from standard references based on the construction material of the channel, and its condition. These n-values have been experimentally determined for various materials and are available in tabular form. However, these values are true for water only and should not be used directly for any other fluid. Given the size, shape, slope, and roughness of the channel, an open-channel flow meter can calculate the flow rate using the Manning formula based on a measurement of the liquid depth. The Manning formula is not as accurate as the hydraulic structures but offers an advantage that no weir or flume is required. Typical flow-measuring principles and requirements are illustrated in Fig. III/1.0.1-2. The figure also provides typical mathematical expressions pertinent to typical geometrical shapes for convenient flow calculations.



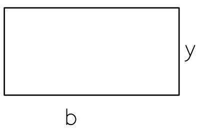
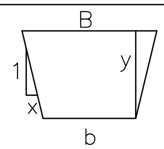
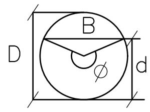
PARAMETER	RECTANGLE	TRAPEZOID	CIRCLE
FIGURE ILLUSTRATION			
AREA A	b.y	(b+xy)y	$1/8(\phi + \sin\phi)D^2$
WETTED PERIMETER WP	b + 2y	$b+2y\sqrt{(1+x^2)}$	$1/2D\phi$
TOP WIDTH B	b	b+2xy	$(\sin\phi/2)D$
HYDRAULIC RADIUS R (A/WP)	b.y/(b+2y)	$\frac{(b+xy)y}{b+2y\sqrt{(1+x^2)}}$	$1/4(1-\frac{\sin\phi}{\phi})D$
MEAN DEPTH Dm HYDRAULIC (A/B)	y	$\frac{(b+xy)y}{b+2xy}$	$1/8D(\phi-\sin\phi)$ / $\frac{\sin\phi}{2}$

FIGURE III/1.0.1-2 Flow by hydraulic radius.

- *Area velocity method:* In the area velocity method, the flow rate is computed by multiplying the area of the flow by its average velocity measured using various methods, e.g., the ultrasonic method. This type of measurement is often referred to as the continuity equation. Actual flow velocity is measured by an ultrasonic transducer while any pressure transducer can measure the level in the channel. The flow meter electronics converts this level into the area of the flow based on the size and shape of the channel. This area is multiplied by the flow velocity to compute the flow. This method does not require any hydraulic structure like a weir or control flume and can be used to measure flow under a wide range of conditions such as:
  - Open channel;
  - Surcharged;
  - Full pipe;
  - Submerged;
  - Reverse flow.
- *Volumetric tank method:* Here the time required to fill a tank of a known volume is determined to compute the flow rate. The volumetric tank method may be effective and economic in the case of small flows for a point-specific measurement. The simple equation q = V/t serves the purpose. Here q is the volume flow rate; V is the known volume; and t is the time unit. This may be effective for:
  - Point-specific flow measurements;
  - Flow measurements where the flow rate is steady;
  - Calibration of primary measuring devices.

  Major advantages of this method include:
  - Speed and simplicity;
  - Its cost-effectiveness.

  This method, however, is not effective for high flow rate (say above 120 m^3/h). There are some other limitations. The major limitations include:
  - Usually limited to measuring smaller flow rates (<100 L/min);
  - Point-specific measurements.

  For large flows, the presence of a regular shape reservoir is required. For measurement, a graduated container, chronometer, tape measure, level indicator, etc. are needed. Another related issue is that measurement is highly dependent on personnel. For small flow measurements, an accuracy of ±1% FSD is achievable.
- *Tracer method:* This method involves quantitative analysis. It measures the changes in the physical or chemical properties of the liquid after soluble substances have been added. So, in this method the dilution rate of a tracer is monitored, when the concentration of the same is known at the intake point. This type of measurement offers almost ±10% accuracy. There are two techniques for tracers; these are the time travel and tracer dilution techniques. The characteristics of the selected tracer is an important issue.

1.0.2 BASICS OF OPEN-CHANNEL FLOW MEASUREMENT

There are many similarities between flow in closed conduits and open channels but there are also some fundamental differences; these will be highlighted in this section so that the understanding is clear. The subject of open channels is a multidisciplinary subject involving civil/structural engineering as well as instrumentation. Therefore, it is necessary that some fundamental details about other disciplines are also taken into consideration.

1. **Energy equation:** From the first law of thermodynamics, which applies for any given system, the change in energy is equal to the difference between the heat transferred to the system and the work done by the system

during a given time interval. The energy, here referred to as the total energy of the system, is the sum of the potential energy, kinetic energy, and internal (molecular) forms of energy such as electrical and chemical energy, etc. In open-channel flow measurement with hydraulic structures, internal energy is insignificant and is normally neglected. In hydraulic applications, the energy of the system is referred to as the terms of "head." Therefore, the energy at any point in a hydraulic system can be expressed as the pressure head (p/γ), elevation (Z) head, and velocity ($v^2/2g$) head, already covered in Chapter I, i.e., $p/\gamma + v^2/2g + z = $ constant, where p, v, and z stand for pressure, velocity, and elevation, respectively, and γ is the specific weight in N/m^3 This has been illustrated in Fig. III/1.0.2-1. Let the pressure head p/γ be replaced by Y, as normally referred to in open-channel hydraulics.

Apparently, it may seem that the point at the surface of water in an open channel will have a pressure head that is zero, but on account of elevation there will be flow and at the bottom there will be a positive head (with a difference between the two points).

So, if we look at the figure one gets that at A and B the energy will be A: $z_1 + Y_1 + v_1^2/2g$ at B: $z_2 + Y_2 + v_2^2/2g$ from Bernoulli's theorem A = B, i.e., the energy at both sides is the same. Here there will be additional heads corresponding to pumping and that for the frictional loss, so for the entire system the energy equation will be

$$z_1 + Y_1 + v_1^2/2g + H_g = z_2 + Y_2 + v_2^2/2g + H_l \quad \text{(III/1.0.2-1)}$$

here H_g is the energy gain due to pumping, and H_l represents the head loss due to friction. So far nothing new has been discussed from what has been covered in Chapter I, except the concept of head gain and head loss in the system. In the case that the fluid flow is due to gravity, be it in a closed circuit or open channel, there will be no head gain ($h_g = 0$), but a small loss due to friction, as shown in Fig. III/1.0.2-1, will be present.

2. **Hydraulic grade and energy grade:** The hydraulic grade represents the head as a sum of pressure head and elevation (i.e., $z_1 + Y_1$ or $z_2 + Y_2$ represent the hydraulic grade in the upstream and downstream, respectively). For open-channel flow the hydraulic grade elevation is the same as the water surface elevation (because the surface pressure is zero) as shown. When the hydraulic grade is

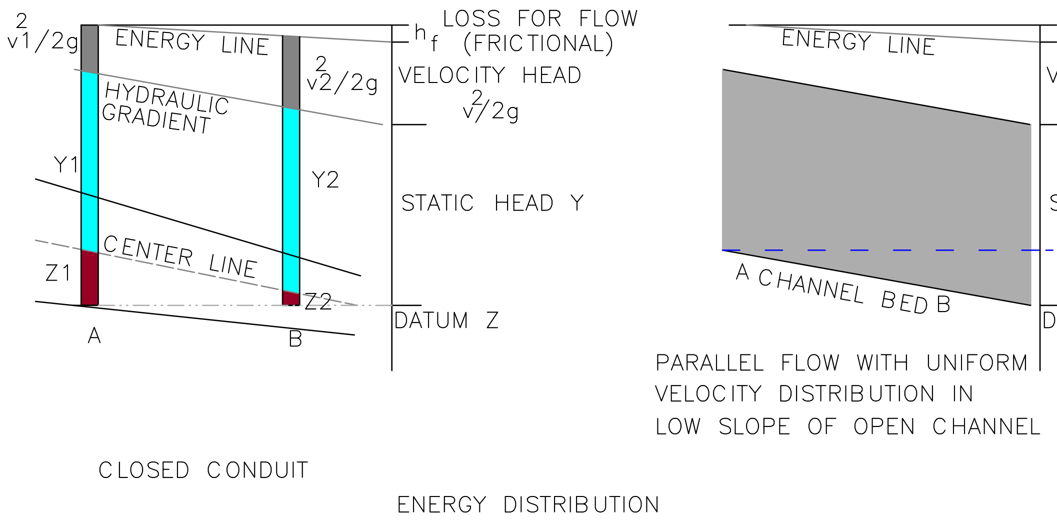


FIGURE III/1.0.2-1 Closed conduit versus open channel flow.

plotted as a profile along the length of flow it is known as the hydraulic grade line (HGL). When the velocity head ($v^2/2g$) is added to the hydraulic grade it is referred to as the energy grade and any plotting of the profile along the length of flow is referred to as the energy grade line (EGL). For lakes and ponds where velocity is zero, HGL = EGL.

3. **Closed conduit versus open-channel flow:** From the discussions above EGL and HGL have been conceived of and it has also been established that there may be a small loss of energy due to friction and this same energy will be converted into heat and is represented by h_f in the figure. On the right-hand side of the figure an open channel has been depicted, in this let the flow be parallel with uniform velocity distribution, from the figure it can be seen that HGL is the same as the water surface which is at atmospheric pressure. There is a similarity between the two, however, the major difference is that the flow in a closed conduit is influenced by pressure in the line, whereas in an open channel it is influenced only by gravity. And, in the case of a closed conduit, fluid does not come into contact with the atmosphere, whereas in an open channel it is in contact with the atmosphere. It is comparatively easier to measure flow in a closed conduit than in an open channel, mainly because the position of the free surface frequently changes with time as well as space. The major differences in flow measurements between a closed conduit and an open channel are listed in Table III/1.0.2-1.
4. **Open channel types:** Open channels can be classified in different ways. These are:
   - *Prismatic and nonprismatic channels:* Channels can be broadly classified as prismatic and nonprismatic. A channel with a constant cross-section and bottom slope with fixed alignment is referred to as a prismatic channel. Any channel which does not follow any of the above criteria is referred to as a nonprismatic channel.

TABLE III/1.0.2-1 Flow Measurement Closed Conduit Versus Open Channel

Point of Difference	Closed Conduit Flow	Open Channel Flow
Driving force	Hydraulic pressure inside	Gravity-driven
Cross-section	Known cross-section normally round/ regular shape	May be unknown on account of variation in depth
Calculation basis	Continuity equation	Continuity as well as momentum balance
Special condition	Nothing specific	Free surface at atmospheric pressure
Roughness	There may be roughness but it can be handled	It is difficult to handle the roughness
Parameter variations	Flow and velocity variations are present	Flow and velocity variations are great. Depth: A few cm to >10 m in river; velocity: 0.1 to 50 m/s; flow: a few L/min to >10,000 m^3/s in river spillway
Rate of change of head with flow	Rate of change of head against rate of change of flow (head type flow) is small, especially near the end	Rate of change of head against rate of change of flow (head type flow) is large, especially near the end

- *Natural channel:* A river is an example of a natural channel. Natural channels or sections are in general very irregular, can be of any form, and can vary from parabolic to an approximate trapezoid shape [3]. If there are variations along the length of the channel, these are nonprismatic. Also, construction materials can have wide variability as the ground can have many different properties. There can also be variations in surface roughness with time and elevation. Added to these, the boundary is not fixed due to deposits of sediment or erosion. Therefore it is quite difficult to analyze these channels accurately. The channel may consist of a main channel section carrying normal discharges and one or more side channel sections to accommodate overflows. These are called compound channels.
- *Artificial channel:* Artificial/man-made channels, such as irrigation/navigation channels, on the other hand, are usually designed with sections of regular geometrical shapes. Normally length regularity is maintained throughout, so these are prismatic channels. Common geometrical shapes include rectangular, trapezoidal, triangular, circular, parabolic channels, etc. to name but a few. Usually they are made from concrete and steel. On account of the defined geometrical shapes it is easier/simpler to analyze with better precision.

5. **Related parameter:** Under this subsection some of the commonly used related terms discussed above are explained for better clarity. There are two parts in the discussions: one is the dimensional details and the other is flow types. For dimensional data the table in Fig. III/1.0.1-2 may be referred to. In this table, the details for commonly used geometrical shapes have been illustrated with symbols. These are further explained in Fig. III/1.1.1-1.

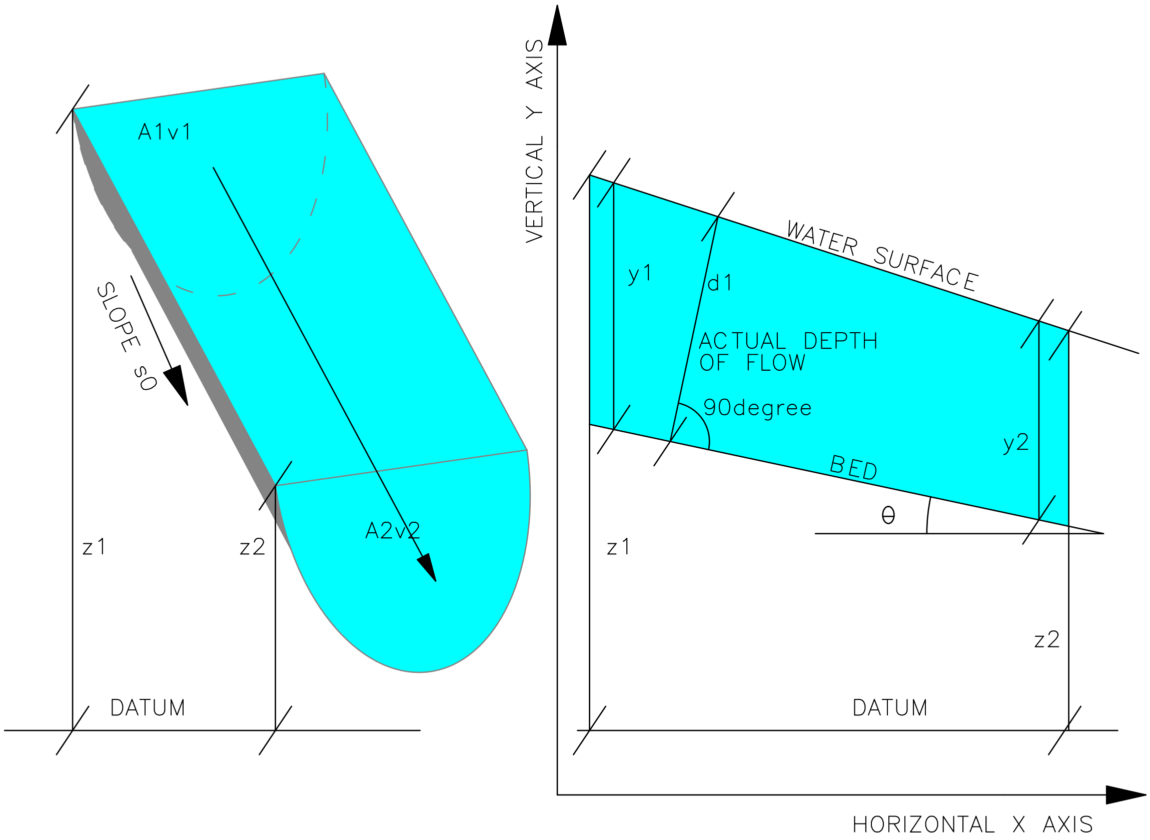


FIGURE III/1.1.1-1 Continuity of volume slope and depth of flow.

- *Depth (y):* The vertical distance from the water surface to the lowest point of the channel cross-section is referred to as the depth. In reality, this is little different from flow depth, which is the distance from the bottom of the channel to the water surface perpendicular to flow. In the figure it is illustrated by d for a slope of channel θ with x axis as shown.
- *Stage (z):* The vertical distance from the water surface to any fixed datum is called the stage.
- *Area (A):* This refers to the area of flow which is perpendicular to the direction of flow.
- *Wetted perimeter (WP or P):* The length of the weighted surface perpendicular to the direction of flow.
- *Surface width (B):* Width of the channel section at the free water surface.
- *Hydraulic radius (R):* Ratio of area (A) and wetted perimeter (WP), A/WP.
- *Mean hydraulic depth (Dm):* Ratio of area (A) and surface width (B), A/B.

1.0.3 SELECTION FOR OPEN-CHANNEL FLOW MEASUREMENT

In Subsection 1.0.1.4 it can be seen that there are a number of methods which can be deployed to measure flow in an open channel. Therefore, one should be aware of the selection of a suitable method for this particular application. According to the *USRB* document [4], major selection points are:

- Accuracy requirements;
- Cost;
- Legal constraints;
- Range of flow rates;
- Head loss;
- Adaptability to site conditions;
- Adaptability to variable operating conditions;
- Types of measurements and records needed;
- Operating requirements;
- Ability to pass sediment and debris;
- Longevity of device for given environment;
- Maintenance requirements;
- Construction and installation requirements;
- Device standardization and calibration;
- Field verification, troubleshooting, and repair;
- User acceptance of new methods;
- Vandalism potential;
- Impact on environment.

While selecting the primary device it is necessary to give due consideration to a number of issues, namely, *reference measurement*, *location*, *measuring channel/chamber type of measurement* suited for the application, and then the type of *primary device* selection. In the following subsections discussions are provided to cover these aspects with little more details.

1. **Accuracy:** One of the most important considerations is the target or desired accuracy for the measurement system. Normally, in open-channel flow measurement, approximately 5% accuracy is available in the field, although in the laboratory better accuracy is obtainable. However, in the field, maintaining such a level of accuracy usually requires considerable expense and/or effort.
2. **Cost:** Each of the measurement methods has direct cost implications, not only capital costs but also cost of the installation, maintenance, and serviceable life span of the method. Therefore, total cost implications should not be judged solely on the initial cost.
3. **Reference measurement:** One important aspect in open-channel flow meters is reference measurement by scale. Normally all measurements are compared with the same scale and this is considered as the reference measurement and is considered to be accurate. Reference measurement is usually done with the help of a ruler in meters or feet, which is permanently placed at the point of measurement to calibrate the secondary device in situ by taking a flow reading at the point of measurement and comparing the flow meter value with the reference value.
4. **Location:** When selecting the location of a measuring point in an open channel to measure the discharge, the following points need to be considered.

- The measuring point should have facility for measurement of the continuous flow rate of the total liquid discharge.
- The primary device should be chosen in such a way that it allows the measurement of minimum, normal, and maximum flows.
- Branching off should not be made downstream from the measuring chamber.
- The place of measurement must be accessible all year long.
- There should be provision for placement of a minimum number of measurement points, giving due consideration toward the of building and maintenance costs [1].
- The width should not be so narrow that measuring equipment cannot be installed or where it would cause restriction and it should also not be too wide (<10 m).

5. **Measuring chamber:** The selection of a measuring chamber is very important as it is very important when carrying out measurements, and when maintaining and testing the system by personnel. Therefore, depending on applicability, the following criteria should be met with:
   - Based on the *flow rate* and the *primary device* installed, the chamber should be large enough to allow the inspection of the primary device, insertion of a secondary instrument/device(s) and installation of a temporary or permanent automatic sampler as applicable.
   - Governing safety standards for construction and access to enclosed locations must be followed.
   - Suitable controlled ventilation system (if necessary remote control).
   - Safety landing for deep installations (>6 m) with due consideration toward safety [1].
   - There shall be suitable lighting and heating arrangements as necessary for the type of structure.
   - The chamber's inspection hole must have a suitable cover and must be suitable for personnel; being at least 900 mm diameter with a permanent ladder inside the entrance.
6. **Measurement method selection:** The importance of selecting the right method for precise and quality measurement of open-channel flow cannot be overestimated. The following criteria may be considered as guidance, especially for effluent/sewerage flow measurements where there will be additional considerations for the presence of solids and other foreign bodies.
   - Presence of solids in water;
   - Possible accuracy and repeatability as compared to the desired accuracy and repeatability;
   - Range of flow measurement, possible and desired;
   - Fluctuations in discharge and tolerance limit;
   - Pressure drop of the method vis a vis allowable pressure drop;
   - Secondary instrument sensitivity to fluctuation, cost, installation possibility;
   - Precision of secondary instrumentation system—including data processing;
   - Maintenance and maintenance cost of the entire system;
   - Overall cost of installation and maintenance.
7. **Other features:** From the various criteria mentioned, the following two points are of importance from an instrumentation point of view for open-channel flow measurement as they influence measurement precision in a number of ways. It can affect the primary device as well as secondary instruments.
   - *Presence of solids:* There are possibilities for the presence of solids in a liquid to be measured by open channel, especially for effluents. These could be all types of suspended solids of varying shapes and sizes. Solids may deposit upstream of the measuring device, stick to walls, and/or adhere to structures. Upstream deposits would tend to obstruct flow or modify approach velocities. Solids adhering to the walls of a measuring device can distort the geometry and original dimensions. Naturally this would affect the measurement

and bring about inaccuracies—especially for weirs. On account of their flat bottoms and smooth surfaces, flumes are less affected.

- *Fluctuations of flow:* Open-channel measurements are carried out by primary devices and secondary instruments. While selecting secondary instruments care must be taken to ensure their precision and sensitivity towards fluctuations. It is therefore important to verify how systems react during fluctuations. In the control section of a measuring device, a drop or increase in discharge should not cause turbulence and cause the flow rate to vary. Installation of a secondary instrument is also vital.

8. **Units of open-channel flow measurement:** In open channels there are a number of units used, based on the applications, therefore it is better to become familiarized with these units. However, prior to that it is essential to understand the various abbreviations used and their conversion details:
   - cfs = Cubic feet per second = 450 gpm = 02832 cms;
   - cms = Cubic meters per second = 35.31 cfs;
   - gpm = Gallons per minute = 0.00223 cfs = 0.06309 L/s;
   - L/s = Liters per second = 15.85 gpm.

   Commonly used units are listed in Table III/1.0.3-1.

TABLE III/1.0.3-1 Units of Measurement

Frequency	US/Imperial Unit	Metric Unit
Frequently	Gallons/min or gallons/day or cfs	Cubic meters per day, liters/sec (L/s)
Occasional	Million gallons per day, gallons per hour	Cubic meters per hour, cubic meters per min, liters/hour

1.0.4 PRIMARY DEVICE SELECTION AND INSTALLATION

There are two types of primary devices used in open-channel flow measurements. These are weirs and flumes, which again available in several versions. In this section short discussions on the features of each of them appear and brief guidance is provided for selection of primary devices for open-channel flow measurement. At the end, short discussions are provided on installation guidelines.

1. **Weir:** The weir is one of the simplest structures used in open channels and can be erected across the channel to measure the discharge of liquid. A thin-plated weir is a 3−6-mm thick plate with a straight edge (crest), or a thick plate with 45 degrees angle edges (Fig. III/3.1.0-1B). When placed across the flow liquid is forced over the plate or into a V-notch in the weir. The edge over which water flows is called the *crest*. The height of the discharge over the crest is called the *nappe*. Weirs are named based on their shape, i.e., v notch weir, triangular weir, etc. Flow is computed by simply measuring the vertical height, between the bottom of the notch (crest) and the surface of the water, at a *determined distance* upstream from the weir using the calculation formula applicable for the shape and size of the weir. For a particular size and shape weir, in free flow or stable flow conditions, there is *only one* water depth upstream for a particular weir, so measurement is reliable.
2. **Flume:** Prefabricated flumes are installed in a flow system. These are molded open sections that put a restriction on the flow path. The flat bottom type provides contraction through side walls, and Parshall flumes provide restrictions in flow lines. By this restriction there is an increase in velocity, and hence an increase in level changes. There are three sections, the Venturi (converging) section, the throat section, and the diverging section. These are calibrated as per the manufacturer's data.

TABLE III/1.0.4-1 Advantages and Disadvantages of Primary Devices

Primary Device	Advantages	Disadvantages
Weir	**1.** Inexpensive **2.** Can be applied for wide flow range **3.** High precision is possible when recommendations are followed for manufacturing and installation **4.** Easier to inspect and detect abnormalities	**1.** Loss of depth and backwater effect **2.** Regular maintenance and inspection required **3.** Solid deposits in the upstream
Flume	**1.** Wide range of flow **2.** Self-cleaning and prevent sedimentation **3.** Low pressure drop **4.** Reliable free and submerged flow	**1.** Expensive **2.** Careful for installation **3.** Require water-tight base **4.** Requires even distribution at entrance

3. **Comparison of primary devices:** For comparison of two primary devices advantages and disadvantages of each of them are enumerated in Table III/1.0.4-1.
4. **Selection of primary device:** After going through the above discussions it can be argued that flumes are generally preferred over weirs, due to their numerous advantages, namely lower pressure drops and self-cleaning facilities. When cost is a factor, a weir is better choice because the capital cost and installation cost of flumes are higher than for weirs. However, this cost difference should be weighed against requirements for maintenance and inspection cost and head loss for weirs. Where there is the possibility of solid deposits this can affect the measurement by weirs as it can modify the approach velocity. Therefore, selection should be based on the design criteria for a particular application.
5. **Installation requirement:** The following general guidelines may be followed for the installation of primary measuring devices:
   - Primary flow devices must be properly aligned with the direction of flow.
   - Primary flow devices should be in a straight section of the flow channel.
   - The primary device approach section should be free from any branch line, curves, heads of water, or abrupt changes in the channel bottom.
   - Primary devices with stilling wells are recommended. Stilling wells should be connected to the primary device. They must be positioned in locations where water depth measurements are taken in the flume. Stilling wells should be wide enough to allow a flow meter level detector to be installed and operated and the well to be cleaned [1].
   - To avoid the backwater effect, the channel should have enough capacity for water discharge.
   - There should a staff gauge (ruler) permanently placed at the measuring point.

1.1.0 Fluid Mechanics of Open Channels

In previous discussions it was stated that there are many similarities between the flows in a closed conduit and in an open channel, but there are some fundamental differences between the two. In this section, brief discussions on fluid mechanics in open channel has been covered. Again the basic

laws of physics will be the same. So what will happen is that there will be some modification in the formula associate with closed conduit flow on account of changes in the physical conditions for open-channel flow. A simple issue is that in the case of an open channel force will not be pressure but gravity, as the water surface is open, the frictional force will be different. In this section a short discussion on fluid mechanics pertaining to open channels is covered. Major issues which govern this discussion include the conservation laws of physics, i.e., conservation of mass—continuity, conservation of momentum—force and conservation of energy—various heads and elevations.

1. **Conservation of mass:** This law of physical chemistry states that mass cannot be created or destroyed; it can only be converted from one form to another by a chemical reaction. As there is no chemical process involved in the process we discuss, the mass entering the channel must be equal to that leaving the channel. This gives us the continuity equation for flow.
2. **Conservation of energy:** This law states that the total energy in a system cannot be increased or destroyed; it can only be converted from one form to other. This is the fundamental concept of Bernoulli's equation. During flow potential and pressure, energies are converted into kinetic energy. This physical phenomenon could be exploited to compute flow with the help of various heads and elevation.
3. **Conservation of momentum:** This comes from Newton's first and second laws of motion. A moving body will continue to move with the same velocity until subject to an external force. And from the second law we get: when there is an external force it will cause a change in momentum. This gives us the concept of force in an open channel which causes flow to occur and where there will be changes in velocity in the inlet and outlet.

In the subsections that follow these will be discussed with suitable short explanations.

1.1.1 CONTINUITY EQUATION FROM CONSERVATION OF MASS

This discussion starts with an arbitrary small control volume in the channel as shown in Fig. III/1.1.1-1 with uniform and steady flow over a very small time difference Δt. Here, for the purpose of easier explanation, steady (not changing with time) and uniform (not changing with space) flow is considered. However, this is true as long as control volume and time are very small. Since the volume is fixed, so from the conservation of mass, for a noncompressible fluid (liquid) one gets that mass entering and leaving the control volume shall be the same.

If q_{inlet} and q_{outlet} are the volume rate entering and leaving the control volume in the time interval Δt and ρ are the density of the liquid then from conservation of mass one gets

$\rho q_{inlet} = \rho q_{outlet}$; if A_1 and A_2 are the arbitrary area at inlet and outlet, and v_1 and v_2 are the velocity of the liquid entering and leaving the control volume then,

$q_{inlet} = A_1 v_1$ and $q_{outet} = A_2 v_2$ so applying this to the conservation mass equation one gets

$$\rho A_1 v_1 = \rho A_2 v_2 \quad \text{or} \quad A_1 v_1 = A_2 v_2 \qquad \text{(III/1.1.1-1)}$$

These are used in computation of flow as shown in Chapter I. Compare Eq. (III/1.1.1-1) with Eq. (I/2.1.1-1) for flow in a closed conduit.

1.1.2 CONSERVATION OF ENERGY

Bernoulli's theorem is based on this concept and has been discussed at length in Chapter I and so is not repeated here. In this connection, Subsection 1.0.2.1 of this chapter may be referenced. As there is no pumping and no head gain, Eq. (III/1.0.2-1) reduces to

$$z_1 + Y_1 + v_1^2/2g = z_2 + Y_2 + v_2^2/2g + H_l \qquad \text{(III/1.1.2-1)}$$

Often H_l is represented by h_f as head loss due to friction discussed subsequently.

1.1.3 MOMENTUM FORCE AND VELOCITY DISTRIBUTION

Let us consider the control volume during Δt; from Section 1.1.1

Mass at the entrance/inlet $= \rho A_1 v_1 \Delta t$; momentum $= \rho A_1 v_1 \Delta t.\ v_1 = \rho q_{inlet}.\ \Delta t v_1$

Mass at the leaving/outlet $= \rho A_2 v_2 \Delta t$; momentum $= \rho A_2 v_2 \Delta t.\ v_2 = \rho q_{outlet}.\ \Delta t v_2$

For liquid, ρ is the same in both cases and from Section 1.1.1 it is seen that $q_{inlet} = q_{outlet} = \Delta q$ (say).

However as v_1 and v_2 are different, so the momenta are not equal.

From Newton's first law it is known that a change of momentum of a moving body is possible only when there is an external force. Newton's second law gives the quantitative account of force; force = rate of change of momentum. So in this case the change in momentum gives rise to force. Therefore,

ΔF = change in momentum/Δt or, $\Delta F = \rho \Delta q\ (v_2 - v_1)\ \Delta t/\Delta t$. Here this force is basically from gravity. In an inclined plane there will naturally be components of these forces in different directions based on the configuration and orientation of the control volume chosen. So, in generalized terms, force vector is the sum of force along three axes $\vec{F} = \vec{F_x} + \vec{F_y} + \vec{F_z}$

So, F_x could be specified as

$$F_x = \rho q(v_{2x} - v_{1x}) \qquad \text{(III/1.1.3-1)}$$

In deducing the above equation, as well as for the energy equation, it has been assumed that there will be uniform velocity over the cross-section. In practice this is not the case as there will be variations in velocity across the cross-section. Also, such variations are asymmetrical about any axis. In the case of a closed conduit, there will be variations in velocity but these are symmetrical about the central axis. On account of free water surface, where there will be zero shear force, maximum velocity is expected there. However, in reality, maximum velocity is found just below the water surface. This is due to the presence of a *secondary current* which travels from the water surface toward the center and due to resistance at the interface of water and air. The typical velocity distribution in an open channel has been illustrated in Fig. III/1.1.3-1. It can be seen that the maximum velocity is available just below the surface, and as one goes towards the center. If v_m is the maximum velocity at a point just below the surface, the velocities of other layers have been shown as a fraction of the maximum velocity. The boundary resistance modifies the velocity distribution. The velocity near (just below) boundaries is less than the velocity at a distance from the boundaries. Furthermore, for flow through sudden expansions/contractions or through natural channels or varying cross-sections there will be velocity distortion that causes errors. To circumvent this problem, the energy coefficient and momentum coefficient are used. A short discussion has been presented on the coefficient of momentum and coefficient of energy in the following section.

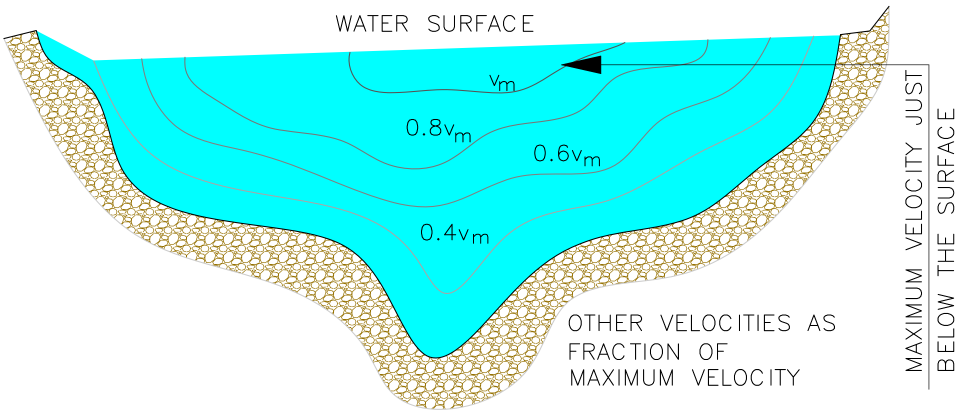


FIGURE III/1.1.3-1 Velocity distribution in an open channel (typical).

1.1.4 ENERGY COEFFICIENT AND MOMENTUM COEFFICIENT

Take a small section of area dA and velocity v. The weight of flow through an element of area dA is equal to ρvgdA. Hence, kinetic energy = $\rho vgdA \cdot v^2/2g = 0.5\ \rho v^3 \cdot dA$. So, to get the total weight over entire area it is to be integrated from 0 to A.

$$\text{Total energy} = 0.5 \int_0^A \rho v^3 \cdot dA$$

If V is the average velocity and A the area, then total kinetic energy will be $= 0.5\rho V^3 \cdot A$.

Therefore,

$$\text{coefficient of energy } \alpha = \frac{0.5 \int_0^A \rho v^3 \cdot dA}{0.5 \cdot \rho A \cdot V^3} = \frac{\int_0^A v^3 \cdot dA}{AV^3}$$

(III/1.1.4-1)

Similarly, in the same manner the coefficient of momentum can be derived and expressed as

$$\text{Coefficient of momentum } \beta = \frac{\int_0^A v^2 \cdot dA}{AV^2}$$

(III/1.1.4-2)

So for practical purposes, the velocity head is multiplied by the corresponding coefficient.

Hence Eq. (III/1.1.2-1) can be rewritten as

$$z_1 + Y_1 + \alpha v_1^2/2g = z_2 + Y_2 + \alpha v_2^2/2g + H_l$$

(III/1.1.4-3)

where Y is pressure head, z is elevation, and $H_l = h_f$ for loss treated later.

Similarly, force from the momentum equation, Eq. (III/1.1.3-1), can be rewritten as

$$F_x = \rho q \beta (v_{2x} - v_{1x}) \quad \text{(III/1.1.4-4)}$$

These coefficients can be computed theoretically with mathematical formulae or can be found graphically. Table III/1.1.4-1 presents typical values and ranges for the above coefficients.

In view of the limited space available in this chapter, only a short discussion has been presented here. Interested readers may go through standard books on hydraulics or read Refs. [5,6].

1.1.5 REYNOLDS NUMBER AND OPEN-CHANNEL FLOW CLASSIFICATION

From Subsection 1.1.2.6 of Chapter I it can be seen that there are three categories of flow: Re < 2000 (2300): laminar; 2000 < Re < 4000: transitional; and Re > 4000: turbulent flow.

From Fig. III/1.0.1-2 one gets that hydraulic radius R = A/P. Now, for a full-flow circular pipe $A = \pi D^2/4$ and wetted perimeter P = πD; so, R = D/4

So,

$$Re_{channel} = \frac{\rho \nu R}{\mu} = \frac{\rho \nu D}{4\mu} = Re_{pipe}/4$$

(III/1.1.5-1)

So, $Re_{channel} < 2000/4$; <500: laminar flow: $Re_{channel} > 4000/4$; >1000: turbulent flow.

It is worth noting that turbulent flow in an open channel is not so well defined for open channels as for closed conduits. Having established the friction formula, it is time to look at

TABLE III/1.1.4-1 Typical Values and Ranges for α and β [5]

Channel Type	α Range	Average α	β Range	Average β
Regular channels, flumes, spillways	1.10–1.20	1.15	1.03–1.07	1.05

another important aspect found in all types of flow. This is friction, which will be discussion in the following subsection.

1.1.6 FRICTION EQUATIONS AND ROUGHNESS COEFFICIENT

In this section various equations are used for different flow types. Let us start with uniform flow which does not change with space, i.e., along a channel. Let us take a small section with length L, with arbitrary area A considered in an open channel which is at an angle θ with a horizontal line. This has been depicted in Fig. III/1.1.6-1.

In this section of a uniformly flowing open channel, there are two forces acting on the small flow section considered. These two forces are gravitational force arising out of the weight of the section and force due to friction.

Gravitational force is the component of the weight of the section along the flow direction and is balanced by the frictional force opposing it along the same line in the opposite direction.

Gravitational force component: area·length·density·g·sin θ = A·L·ρ·g·sin θ.

There will be shear force along the channel bed and walls.

So, if τ is the shear stress then the force will be = τ·L·P

For balancing

$$A \cdot L \cdot \rho \cdot g \cdot \sin\theta = \tau \cdot L \cdot P$$

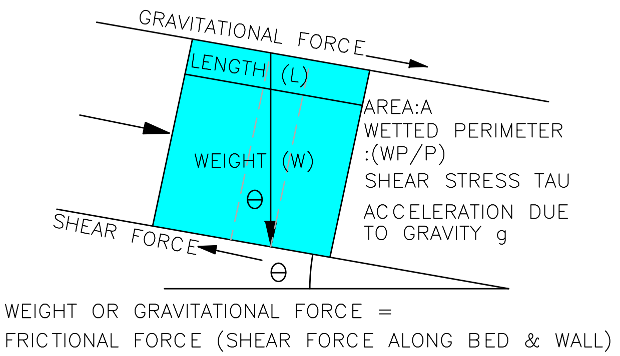


FIGURE III/1.1.6-1 Force balance in an open-channel flow.

or

$$\tau = A \cdot \rho \cdot g \cdot \sin\theta / P \qquad \text{(III/1.1.6-1)}$$

Normally channels have small slopes like 10–12 degrees or so, meaning 1:50, therefore the slope (S_0) can be estimated as

$$S_0 = \sin\theta = \tan\theta \qquad \text{(III/1.1.6-2)}$$

In view of this, shear stress can be estimated when the slope is given by combining Eqs. (III/1.1.6-1 and III/1.1.6-2) in terms of slope and hydraulic radius R (=A/P)

Therefore

$$\tau = (A \cdot \rho \cdot g \cdot S_0)/P \quad \text{or} \quad \tau = \rho \cdot g \cdot R \cdot S_0 \qquad \text{(III/1.1.6-3)}$$

Having devised a means for shear stress estimation, one can look to find the frictional losses and relate the shear stress friction to the velocity.

There are a number of laws governing friction losses. These are:

- Manning's equation;
- Chézy's (Kutter's) equation;
- Darcy–Weisbach equation.

Now let us have a close look at these laws.

1. **Manning's equation:** Manning's equation is the most commonly used open-channel flow measurement. This is the formula used for open-channel flow by slope and hydraulic radius method. The roughness is represented by a Manning's roughness value, n. The experimental value of n is available, which can be used only for water not for any other fluid. Manning's equation is:

$$v_{mean} = V = \frac{K}{n} \cdot R^{2/3} S_0^{1/2} \qquad \text{(III/1.1.6-4)}$$

$V = v_{mean}$ = mean velocity (m/s, ft/s); K = 1.49 for FPS units, 1.00 for SI units; n = Manning's roughness value; S_0 = slope (say 1:50); R (=A/P) = hydraulic radius (m, ft); (v_{mean} has been represented in V in Eqs. (III/1.1.4-1 and III/1.1.4-2), so V is

used here). Multiplying both sides of Eq. (III/1.1.6-4) by A one gets $v_{mean} \cdot A = \frac{K}{n} \cdot A \cdot R^{2/3} S_0^{1/2}$ or $q = \frac{K}{n} \cdot A \cdot R^{2/3} S_0^{1/2}$ which is Eq. (III/1.0.1-3). Now replacing R with A/P, one gets:

$$q = \left(\frac{K}{n} \cdot A^{5/3} \cdot S_0^{1/2} \right) \Big/ \left(P^{2/3} \right) \qquad \text{(III/1.1.6-5)}$$

2. **Chézy's (Kutter's) equation:** For the state of rough turbulent flow Chézy's (Kutter's) equations can be used, especially for the design of sewer systems. The basic consideration is that for rough turbulent flow, shear stress is proportional to the square of mean velocity $\tau \propto v_{mean}^2$. Therefore $\tau = K \cdot v_{mean}^2$. Here K is the proportionality constant. Now putting the value of τ from Eq. (III/1.1.6-3) one gets $\tau = \rho \cdot g \cdot R \cdot S_0 = K \cdot v_{mean}^2$ or, $v_{mean} = (\sqrt{RS_0})$ if $C = \sqrt{\frac{\rho g}{K}}$ here K, ρ & g are constant then

$$v_{mean} = C\sqrt{RS_0} \qquad \text{(III/1.1.6-6)}$$

Eq. (III/1.1.6-6) is known as Chézy's (Kutter's) equation. Here the roughness component, C, is a function of the hydraulic radius, slope, and lining material of the channel. In this case C has been related to Manning's n coefficients by Kutter's equation involving slope and hydraulic radius. For this, Eq. (III/1.1.6-6) is known as Chézy's (Kutter's) equation.

3. **Darcy–Weisbach equation:** In Chapter I, it was established that the flow of liquid through a pipe is resisted by viscous shear stresses within the liquid layers and the turbulence at the internal walls of the pipe, due to the roughness of the pipe material. This is pipe friction and is measured in terms of head of fluid expressed in meter or feet. The phenomenological equation which is used to relate the head loss, or pressure loss, due to friction along a given length of pipe to the average velocity of the fluid flow for an incompressible fluid was named after Henry Darcy and Julius Weisbach. The Darcy–Weisbach equation is basically meant for pressurized pipe systems, but it can be applied equally to any flow rate and any incompressible fluid, in open channel flow systems also. However, this has not yet been widely accepted because the solution to the equation is difficult and not easily computed. The roughness component in the Darcy–Weisbach equation is a function of both the channel material and the Reynolds number, which vary with velocity and hydraulic radius [3]. Much research has been carried out over many years and various formulae created to calculate head loss. Among these are Chézy's (Kutter's) equation and Manning's equation discussed above. Weisbach proposed the equation for direct head loss measurement, popularly known as the Darcy–Weisbach formula or Darcy–Weisbach equation as shown in Eq. (III/1.1.6-7).

$$h_f = \frac{fLv^2}{2gD} \qquad \text{(III/1.1.6-7)}$$

where h_f = head loss (m/ft); f = Darcy friction factor; L = length of pipe (m/ft); d = inner diameter of pipe (m/ft); v = velocity of fluid (m/s/ft/s); g = acceleration due to gravity ($m/s^2/ft/s^2$).

Fanning did much experimentation to provide data for friction factors, however, the head loss calculation using the Fanning friction factors f_f has to be applied using the hydraulic radius (not the pipe diameter). The hydraulic radius calculation involves dividing the cross-sectional area of flow by the wetted perimeter. For a round pipe with full flow the hydraulic radius R is equal to ¼ of the pipe diameter (R = D/4) and here the Fanning friction factor f_f is ¼ of the Darcy friction factor f, so Eq. (III/1.1.6-7) becomes

$$h_f = \frac{f_f}{4} \cdot \frac{4Lv^2}{2gR} \text{ or, } h_f = \frac{f_f}{2g} \cdot \frac{Lv^2}{R} \qquad \text{(III/1.1.6-8)}$$

From Fig. III/1.0.2-1 it can be seen that there is a direct relation between h_f and L, as slope $S_0 = h_f/L$, so,

$$S_0 = \frac{f_f}{2g} \cdot \frac{v^2}{R} \qquad \text{(III/1.1.6-9)}$$

The Colebrook−White equation provides a mathematical method for calculation of the friction factor. This is mainly applicable for pipes.

After all these formula have been discussed, it is important to note another factor K, known as channel capacity, given by $K = ACR^{1/2}$ (all symbols have the meanings discussed above).

4. **Roughness coefficient:** For the convenience of the reader lists of roughness coefficient for various channels and materials are given below in Tables III/1.1.6-1 and III/1.1.6-2.

TABLE III/1.1.6-1 Manning Coefficient Range Different Channels

Channel	Surface Specification	Manning's n Range
River	Earth straight	0.02−0.025
River	Earth meandering	0.03−0.05
River	Gravel straight/ winding	0.03−0.08
Canal	Unlined earth/rock	0.18−0.025/ 0.025−0.045
Lined canal	Concrete	0.012−0.017

TABLE III/1.1.6-2 Roughness Coefficient for Common Materials in Different Forms

Materials	Manning Coefficient (n)	Darcy−Weisbach Height (mm)
Asbestos, brass, concrete (steel), Cu, glass, Pb	0.011	0.0015
Concrete wooden form	0.015	0.6
Galvanized iron	0.016	0.15
Steel (new unlined)	0.011	0.045
Steel riveted	0.019	0.9

1.1.7 SPECIFIC ENERGY

Channels do not always flow at normal/particular depths. It is therefore necessary to focus on another important concept—specific energy (normally represented by E_s). Specific energy could be defined as the energy of flow with reference to the channel bed as the datum. So, with reference to the channel bed when there is an open-channel flow, there is a specific energy associated with it, typically as shown in Fig. III/1.0.2-1. Therefore, for any flow section, the specific energy can be mathematically represented by the sum of the depth of flow and the velocity head (see Eq. III/1.0.1-1 also).

$$E_s = y + \frac{v_{mean}^2}{2g} \qquad \text{(III/1.1.7-1)}$$

where E_s = specific energy (m, ft); y = depth of flow (m, ft); v_{mean} = mean velocity (m/s, ft/s); g = gravitational acceleration (m/s^2, ft/s^2). Here, if depth increases then, corresponding to any specific energy level, there will be a drop in velocity. When an infinitely short section of open channel is considered then the general energy equation can be reduced to an equality of specific energies.

$$E_1 = y_1 + v_{mean1}^2/2g = E_2 = y_2 + v_{mean2}^2/2g \qquad \text{(III/1.1.7-2)}$$

Again, if depth increases then, corresponding to any specific energy level, there will be a drop in velocity. Now, the velocity of the section is directly related to the area of flow, and that area of flow is a function of channel depth. This means that, for a given discharge, the *specific energy at each point is solely a function of channel depth*. Let us look

at this with mathematics and an equation applying the energy coefficient.

$$E_s = y + \frac{\alpha q^2}{2gA^2} \quad \text{or } E_s - y = \frac{\alpha q^2}{2gy^2}\cdot\frac{1}{b^2} \tag{III/1.1.7-3}$$

1. **Critical depth:** Looking at a unit slice parallel to the flow direction in a two-dimensional flow. Discharge per unit width q is constant, i.e., $\frac{q}{b}$ = constant. So, Eq. (III/1.1.7-2) can be conceived as $E_s - y = \frac{C}{y^2}$, where C is constant. This is a polynomial of third degree, one of them will be negative, so there will be two sets of solutions. If, for a given flow, channel depth is plotted against specific energy, one gets a curve (Fig. III/1.1.7-1A).

   From the figure it can be seen that for a particular specific energy (at a given discharge) there exist two depths. From the figure, it can also be seen that there exists a depth at which the specific energy is at its minimum value. This depth is called the ***critical*** depth. If the velocity is greater than the critical velocity (that is, the depth is less than the critical depth), the flow is considered ***supercritical***. If the velocity is lower than the critical velocity (the depth is more than the critical depth), the flow is ***subcritical***. The velocity at the critical depth is equal to the **wave celerity (v_c)**. In this connection it is better to recall and compare the definitions of wave celerity supercritical and subcritical definitions given in Subsection 1.0.1.1 above.

   In exactly the same fashion, for a given specific energy if one plots depth against discharge one would get the curve as shown in Fig. III/1.1.7-1B. In Fig. nos. III/1.1.7-1 A & B for particular E_s and q depths have been compared [7]. Thus it is seen that there are three related variables, i.e., E_s, y, and q and their relations can be established by a family of curves as shown in Fig. III/1.1.7-1C. Referring to Fig. III/1.1.7-1 and 2 the properties given in Table III/1.1.7-1 may be noted.
2. **Flow type and Froude number:** Referring to Fig. III/1.1.7-1A and B it can be noted that in the case of subcritical, critical, and supercritical flows (i.e., depth and velocity) Froude's number (Fr) (defined in Subsection 1.0.1.1 in this chapter) has been mentioned. Therefore, the Froude number is another way of deciding the flow type. If $Fr < 1$, it is subcritical and water velocity is less than wave velocity and the important parameter *upstream level* for flow measurement is *affected* by downstream control. In contrast, if $Fr > 1$ it is supercritical and the water velocity is greater than the wave velocity, so the important parameter *upstream level* for flow measurement is unaffected by downstream control. Various flow types and effects of disturbances in transmission are depicted in Fig. III/1.1.7-1E.
3. **Slope design:** In designing the system it is necessary to select proper slope. If, for a given discharge, an arbitrary channel-bottom slope is set then the flow would vary from upstream to downstream and flow would be *nonuniform*. It may be difficult to handle and the flow may erode from one end of the channel and deposit at the other end in its desire to establish uniform flow. For a given discharge, if the increased channel slope is chosen, then there would be a condition in which the flow was relatively shallow at the upstream end and relatively deep at the downstream end. The reverse would be the situation for a decreased channel slope. These have been depicted in Fig. III/1.1.7-1D. So, the obvious question is "*How does one select the slope for uniform flow*?" The answer is simple. From the above discussions, it clear that there are two sets of equations at our disposal: these are $\tau = \rho\cdot g\cdot R$ (Eq. III/1.1.6-3) and $h_f = \frac{fLv^2}{2gD}$ (Eq. III/1.1.6-7). For a given discharge, the

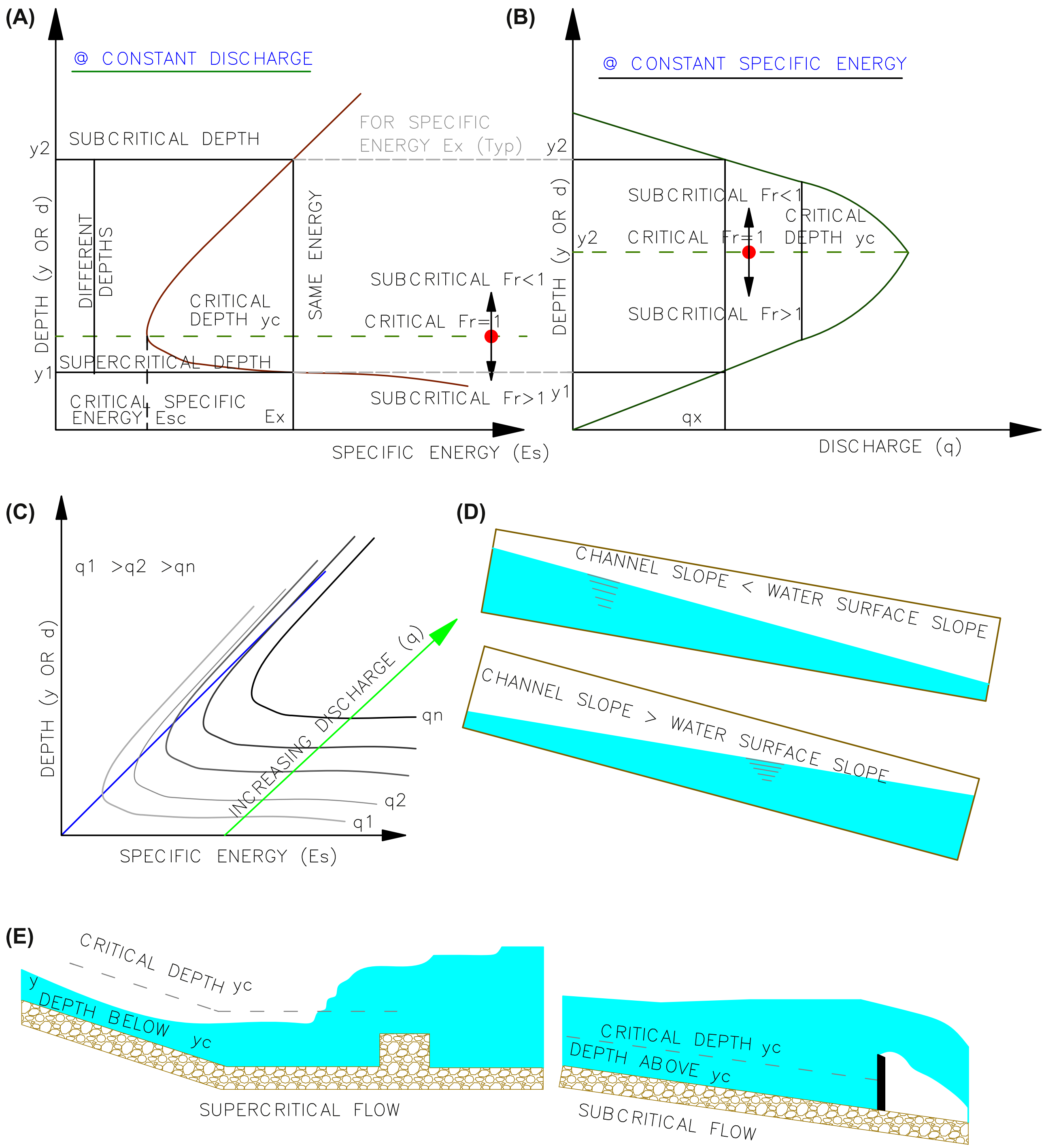


FIGURE III/1.1.7-1 Specific energy in open channel. (A) Depth versus specific energy (at constant q). (B) Depth versus discharge (at constant E). (C) Depth energy and discharge. (D) Channel and surface slope. (E) Open-channel flow and disturbance.

mean velocity v_{mean}, can be found from $Q = v_{mean}yb$ (where b is the known width of the channel). To find f standard values, mean value Reynolds number Re, available data for closed pipes may be used. Now v_{mean} and f could be substituted into Eq. (III/1.1.6-7) to obtain the value of τ. Then, from Eq. (III/1.1.6-3), S_0 can be calculated.

TABLE III/1.1.7-1 Properties of Critical Depth

Conditions	Constant Discharge	Constant Specific Energy
Critical depth, y_c	Specific energy E_{sc} minimum	Discharge maximum q_{max}
Supercritical depth, $y < y_c$	Energy > E_{sc}, **Velocity > v_c**	Flow < q_{max}, **Velocity > v_c**
Subcritical depth, $y > y_c$	Energy > E_{sc}, **Velocity < v_c**	Flow < q_{max}, **Velocity < v_c**

1.2.0 Properties of Open Channels

Based on its origin, as stated earlier, a channel can be classified as either a natural or artificial channel. The cross-sections of natural channels are irregular and hence hydraulic properties may vary from section to section and these are non-prismatic. To study natural channels it is necessary to have knowledge of the hydrology, sediment transportation, etc. Artificial channels, like ditches, drainage, floodways, gutters, navigation channels, power canals, tunnels, spillways, etc. are constructed or developed by mankind. Canals, chutes, culverts, drops, flumes, etc. are different types of artificial channels. Each of them has different properties such as slope, construction materials, etc. A canal is a long and gently sloping channel built into the ground, unlined or lined with stone masonry, concrete, cement, wood, or bituminous materials. Chutes have steep slopes. Culverts are of short length and are mainly used for drainage under roads. A flume is a channel of wood, metal, concrete, or masonry, fiber-reinforced plastic, usually supported on or above the surface of the ground to carry water across a depression. Artificial channels are prismatic channels. Geometrical shapes are used in artificial channels. An unlined trapezoidal section is the most common channel section used in the field as it provides side slopes for stability [8]. Rectangular versions have vertical sides and these are built with a lining such as masonry, rocks, metal, or timber. Triangular shapes are special versions of trapezoidal channels with zero bed width. Precast concrete sections are also used for small canals. Circular shapes are commonly used in sewers and culverts.

1.3.0 Submerged Flow and Submergence Transition

This is an important aspect in open-channel flow measurement. Normally the primary devices such as, for example, Parshall flume/weir are designed for free-flow conditions. The majority of flow/discharge equations are derived from measurement of the upstream head. Now, for some reason the downstream resistance to flow increases to a certain value which could cause a reduction in the velocity through the primary devices and a backwater effect is created. This *transition* from free flow to backwater effect and/or slowing down of velocity is referred to as ***submergence transition***. So, when the downstream depth is raised sufficiently, the flow depth at the crest becomes higher than the critical depth, and ***submerged flow*** conditions exist and flow velocity is subcritical velocity. As stated earlier, the primary device might have been developed for free flow, but due to downstream resistance to flow, i.e., changes in downstream hydraulics, they can submerge the primary device. Such a change in downstream hydraulics can come from deposits of sediment, vegetation, added hydraulic structure, etc. Submergence transition is represented by St and is a measure of the ratio of secondary point head (h_b) to primary point head (h_a). In the case of a Parshall flume, h_b is measured at the throat and primary head h_a is measured at the convergence section. Various primary devices show different St percentages, e.g., the Parshall flume St is between 50% and 80%, while for a broad-crested weir it is 70%–90%. Different sizes of primary devices have different St—ASTD1941 gives St for different sizes of Parshall flume.

With this idea it is better to have two types of artificial channels in two subsequent sections.

2.0.0 FLUME

Of the two primary devices for open-channel flow measurements, flumes are preferred to weirs on account of following points:

- The water must be dammed for flow measurements by weir. This may affect the inflow region.
- On account of approach velocity effects, a large upstream stilling basin is required for weirs.
- In weirs there may be deposits of silt and other solids that might accumulate and alter the measurements.
- Energy loss is smaller compared to that in a weir.

All these relatively negative issues either are not required (dam/stilling basin) for flumes or they are circumvented (debris is driven away) due to the construction of flumes. Also, head losses in flumes are nearly a quarter of those in weirs of the same capacity, and flumes do not have sharp edges or pockets.

Open-channel flumes (applicable to weirs also) are designed in a manner to force a transition from subcritical to supercritical flow. For flumes, the transition is caused by constricting the side walls of flumes to have a narrowing at the throat, raising of the channel bottom, or both. Such construction causes flow to pass through a critical depth at the flume throat. As has already been seen, at the critical depth, energy is minimized as discharge/velocity holds a direct relationship with water depth. However, in flumes it is not easy to measure the critical depth as its exact location is difficult to determine with the varying flow rate. As discussed above, through mass conservation, the upstream depth is related to the critical depth so that discharge can be determined by measuring the reliable upstream depth.

Liquid coming into the flume (in an open channel section) is forced by a bottleneck (shape) created by construction and/or by a subsequent bottom dip, to accelerate. As stated earlier, this acceleration in flow is produced by the convergent sidewalls, raising the bottom, or a combination of both. When only the bottom is raised it is a broad-crested weir as discussed later. With shallow downstream depth and enough convergence between the inlet and outlet of channels, the flow passes through at a critical depth. Therefore, flumes are sometimes called critical-depth flumes. Thus there will be a transition of flow from one regime to another, i.e., river speed motion to rapid speed motion (i.e., it crosses the critical speed). In other words there will be transition from Froude number $Fr < 1$ to $Fr > 1$. When flow passes through a critical depth with unique water surface profile, it gives rise to free flow. Under this condition, upstream heads at a location relative to the control bottom elevation near the region of critical depth are used to determine the discharge. However, due to downstream hydraulics, when there is higher resistance to flow there will be a backwater effect due to submergence transition or submerged flow. To measure discharge with high levels of submergence, two head measurements are required (see Section 1.3.0) and it has accuracy less than for free-flow measurements. The velocity of approach for flumes is a part of the calibration equations which is advantageous compared to a standard weir [4]. The convergence section at the entrance tends to improve the velocity distribution and passage of floating debris. In view of this, it is better for flows containing sediment or solids as it is self-cleaning because of the higher flow velocity. Costly installation of flumes is a major disadvantage.

2.1.0 Flume General Discussions

In this section short discussions cover the main flume types.

2.1.1 FLUME CLASSES

The primary device flume is classified below. For better understanding of the functionality of different types of flumes, several figures have been presented in this book. References to all of these figures are given in Table III/2.1.0-1.

TABLE III/2.1.0-1 List of Figures for Different Flumes

Flume Type	Figure Ref.	Chapter	Flume Type	Figure Ref.	Chapter
Parshall	I/3.1.5-1	I	Parshall	III/2.2.0-1A	III
Venturi	III/2.2.0-2A	III	H Flume	III/2.4.0-1	III
Rectangular	III/2.2.0-1B	III	Trapezoidal	III/2.2.0-1D	III
Palmer−Bowlus	I/3.1.5-2A	I	U Flume	III/2.2.0-1C	III
Cutthroat	III/2.5.0-1	III	Khafaji	I/3.1.5-2B	I

1. **Long-throated flumes:** Long-throated flumes have too long control discharge at the prismatic throat section, with sufficient length in the stream-wise direction to achieve a nearly parallel flow situation and a hydrostatic pressure distribution. Flumes can be rated through proper analysis using fluid flow concepts [4]. The Palmer−Bowlus is a long-throated flume.
2. **Short-throated flumes:** These flumes are named short-throated flumes because they control flow in a region of curvilinear flow. A short-throated flume is characterized by a strong free surface curvature and a departure from the hydrostatic distribution of pressure. The Parshall flume is the most popular short-throated flume. The overall dimensions of the flume are not too short despite being called a short-throated flume. Calibrations for short-throated flumes are determined empirically by comparison.
3. **Special flumes:**
   - *H-flume:* H-flumes are made of simple trapezoidal flat surfaces. These surfaces are placed in such a way as to form vertical converging sidewalls. The downstream edges of the trapezoidal sides are placed so that they form a notch, widening with distance from the bottom. The maximum allowed submergence is 30%.
   - *Palmer−Bowles flumes:* Palmer−Bowles flumes (Wells and Gotaas, 1958) are constructed as inserts with circular bottoms to fit conveniently into U-shaped channels or partially full pipes. These flumes are of the long-throated type.
   - *Cutthroat flumes:* Cutthroat flumes are Parshall flumes with the throat "cut out," hence the name. These flumes are formed by joining a 6:1 converging section with a similar diverging section. They do not have any parallel walls to form a throat. This is a simplified version of the Parshall flume.
   - *Flat-bottomed trapezoidal flumes:* These are flat-bottomed trapezoidal short-form flumes. They were designed to sit flush with respect to the bottom of the incoming channels in an effort to assist sediment movement and allow the canal to drain dry between uses [4].
   - *Special flumes for passing sediment:* These specially designed flumes are designed to combat sedimentation problems, and measure the flow in an open channel. They are supercritical flumes, requiring extensive head drop to operate. They have very limited applications in irrigation.

2.1.2 EXPLANATION OF FLUME GEOMETRY

Normally, flumes have three sections. In the inlet converging section the liquid is forced to accelerate. Liquid enters the converging section in a subcritical state, i.e., typically with Fr around 0.5. The liquid head is normally measured at this section (for submergence it acts as ha discussed earlier). Liquid acceleration takes place mainly at the throat and flow goes to the critical and supercritical stages, i.e., Fr $\geq$ 1. The next section is the divergent

section which slows down the energetic flow to allow the same to the downstream channel. Naturally, where the divergent section is absent the flow will be susceptible to erosion/scour.

2.1.3 PROS AND CONS OF FLUMES

Listed below are the major advantages and disadvantages of flumes.

1. **Advantages:** Following points are a few advantages of flumes.
   - Flumes do not require a dam across the flow line or upstream stilling chamber.
   - They are self-cleaning on account of the higher velocity.
   - For same flow rates flumes have much lower head loss.
   - Flumes offer a wide selection of flow measurement, conditioning, and control options [9].
   - Flumes offer also a wide selection of cross-sections and shapes.
   - Flumes offer moderate accuracy but give dependable and repeatable measurements.
   - There are no sharp edges/pockets and not too many critical dimensions in flumes [10].
2. **Disadvantages:** There a few disadvantages of flume also and these are:
   - A major limitation is the cost of fabrication and installation.
   - Accuracy is highly dependable on the style and type of flume.
   - Flow equations are a little more complicated, especially for certain types, e.g., H type flumes.

2.1.4 SITE CONDITIONS AND ASSOCIATED TECHNICAL ISSUES

Site selection for flume operation is an important issue for open channel flow measurement accuracy. As per USRB recommendations, the flume should be located near the diversion point/the regulating gates used to control the discharge [4]. Good accessibility of flumes is of immense importance from an installation and maintenance point of view. There are a few other considerations that are important, and these are discussed in the following subsection.

1. **Approach conditions:** As stated earlier, in the case of a weir there is a requirement for a stilling chamber, but for flumes there is no such requirement, however, flumes should be away from surging/unbalanced flow or turbulent flow to avoid disturbances in velocity distribution pattern. In the case of such a velocity distribution pattern or poor flow condition, there will be a direct effect on the flow measurement and computation. A tranquil approaching flow is desired for flumes. In this connection, Bos's recommendations may be looked into Ref. [4]:
   - If the control width is >50% of the approach channel, then 10 control widths of straight unobstructed approach are required.
   - If the control width is <50% then 20 control widths of straight unobstructed approach are required.
   - If the upstream flow exceeds the critical velocity, a jump should be forced to occur. In this case, 30 measuring heads of straight unobstructed approach after the jump is completed should be provided.
   - If baffles are used to correct and smooth the approach flow, then 10 measuring heads should be placed between the baffles and the measuring station.
2. **Erosion and scour:** Theoretically, the channel bottom should have stable elevation. However, in reality it may not be possible for this to be maintained. When sedimentation occurs during the dry season, it may be eroded again during the wet season. It is needless to say that sedimentation may modify the approach velocity. Also, due to erosion there may be damage to the foundation of the structure. Therefore the channel water levels and the required sill height, in combination with the discharge versus head relationship of the structure, and the upstream

structure should be assessed [4]. Debris clearing is a solution or where permitted lifting flume could be solution. However latter one needs detailed study.

2.1.5 SUBMERGENCE AND MODULAR FLOW

1. **Submergence:** During the discussions in Section 1.3.0 in this chapter it was noted that in the case of a submerged system for computing the discharge, it is necessary to measure head not only in the upstream but also head at the downstream (at the throat). From Section 1.3.0, it has been noted that in that case pure free flow is not sustained if there is an increase in the downstream resistance due to changes in hydraulic condition. So, all flumes should have a *minimum* head loss to assure free flow, so that only an upstream head measurement is sufficient to determine and compute discharge rate. This minimum required head loss is usually expressed in terms of submergence limit (already mentioned in Section 1.3.0), defined by the *ratio of the downstream head to the upstream head* with the flume throat bottom as reference [4]. Also, it is necessary to gather knowledge about the downstream water surface elevation relation to find out whether there will be any fluctuation due to gate operation and/or if there will be any seasonal changes.
2. **Modular limit:** The term "modular limit" is defined as the limiting submergence ratio for a *particular* flow module, which causes no more than a 1% deviation in the upstream head reading for a given discharge. It is obvious that when these limits are exceeded, an additional downstream head measurement is required to extend the measurement range of a flume, especially for Parshall and cut-throat flumes with lower accuracy. Submergence increases the upstream channel depth, at the cost of upstream velocity. Lower velocity tends to increase the sedimentation problem.

2.1.6 MEASUREMENTS FOR FLOW COMPUTATION

As discussed earlier, free flow head is measured at a suitable point in the upstream, whereas for submerged flow head two points are measured: one upstream (h_a) and another downstream from the throat (h_b). In the following subsection discussions are presented on the methodology of measurement, location of sensors, and sensor types.

1. **Methodology:** The head either upstream alone or at two places can be done either in the channel itself or in a separate stilling chamber/well located on either side of the channel. The stilling well is connected by a pipe of sufficient diameter to the channel, so that there will not be any clogging in the pipe.
2. **Stilling wells:** For accurate discharge measurements, stilling wells are connected to the main channel through holes and pipes to transfer the head and dampen water surface fluctuations by throttling, to obtain better head measurement accuracy. The pipe connecting the stilling well to the flume/canal must be large enough (10% of stilling well diameter) for a quick response to water level changes. The pipe connection to the stilling well should be perpendicular and carefully cut flush with both the canal and the stilling well walls [4].
3. **Location:** According to USRB, the measuring station for short-form flumes must be installed as specified to match closely the location used when the flume was empirically calibrated, e.g., the measuring station of a Parshall flume is in the convergence water surface drawdown [4]. For long-throated flumes the same should be located sufficiently far upstream but close enough for the energy losses between the gagging station and approach section to be negligible. This placement is particularly critical if the ratings are based on coefficient values in a discharge equation.
4. **Selection of the head-measuring device:** There are a number of techniques which could

be adapted for measuring the head for open-channel flow measurement. The decision regarding selection of the technique depends on a number of factors, these are:

- *Purpose of discharge measurement:* This is important because the importance of discharge through sewerage is not the same as that for intake water to a water treatment plant.
- *Frequency of discharge measurement:* As a corollary to the above, it can be said that in some cases measurement can be at fixed times during the day, especially when the change in level is gradual, in contrast to when it is connected to a process plant, where there will be a requirement for continuous measurement. Also, it is necessary to record and monitor these.
- *Detection accuracy:* The accuracy of measurement is also related to the purpose of measurement. When in a process plant, the signal is used in mass balance and therefore the accuracy of measurement has to be high, however such accuracy may not be as important when it is used for sewerage. Since discharge is related to the higher power of the head, the effect will be greater.
- *Structure and sensor mounting:* Each detection system has a different mounting style, therefore the structure of primary device access to mount the device along with its electronics is important. For mounting pressure a sensor space at the bottom is necessary. To insert the capacitance/conductivity probe support of the probe is necessary. These are a few examples to show that due consideration for actual mounting should be taken for sensor mounting.
- *Location and accessibility:* The location is important in the sense that in order to put sophisticated instruments at a remote location one needs to ensure that the necessary utilities are available. If, for a remote installation, a bubbler is selected then one has to first ensure that the instrument quality air is available. Apart from that there should be suitable easy access not only for the sensor, but also for its other electronics. At remote places, electronic transmitters with (say) a fieldbus can be used, but it is necessary to ensure that these are inspected and maintained regularly.

On account of the multipurpose utility of a staff gage (see Subsection 2.1.7.1 in Chapter III) it is normally used in all installations, even if remote sensors are used. The usual expected reading errors in head are listed in Table 8-1 of the USRB manual [4].

2.1.7 HEAD SENSING TECHNOLOGY

There are several technologies which could be deployed to measure the head of the water surface in a stilling well or in the flume channel. In this section only basic technologies are outlined. detailed discussions given later in the chapter. There are four major techniques to measure the head. These are:

1. **Local staff gage:** Staff gages give a quick indication of the level of water in a channel. Periodic readings are taken from a calibrated staff gage. This is used where continuous reading is not necessary (e.g., where the reading change could be gradual), or could be used to compare the results from continuous meter reading. The gage must be placed in a suitable location, size should be such that it could read from a certain distance (say) from the channel bank. The gage should be easy to clean and maintain.
2. **Float-operated mechanical measurement:** There are instances where float-type mechanical instruments are used. These floats go up and down as per the water surface level. For remote transmission, float movements are magnetically coupled to an electronic transducer which produces a standard electronic hardwired signal 4—20 mA DC or data sent via HART protocol/fieldbus recording, data logging, and/or recording/printing.
3. **Hydrostatic pressure sensing:** From basic hydrostatics it is known that, for a

nonpressurizing system like that in open-channel flow measurement, hydrostatic pressure at any point is given by $P = h \cdot \rho \cdot g$. Liquid at normal temperature there will be more or less constant (known) density without much variation, and at a place, g is constant, so $P \propto h$. Therefore, the head can be measured by placing a pressure gage or pressure transducer at the bottom (at a suitable location so that the line is not clogged) of the channel or stilling chamber. The electronic pressure transducer/transmitter produces standard electronic hardwired signal 4–20 mA DC or data sent via HART protocol or by fieldbus data for recording, data logging, and/or recording/printing.

4. **Sealed pressure transducer:** To reduce the chances of the line getting clogged due to debris/sediment, a sealed transducer/transmitter should be used.
5. **Bubbler method:** In the bubbler method, again hydrostatic pressure is measured in the same way as discussed above. However, instead of seals, an air bubbling method is deployed to combat clogging of lines by debris/sediments, etc. These are common in sewerage applications. In this case air is used at a regulated pressure so that it is slightly higher than the possible hydrostatic pressure. Bubbles in the system are set with the help of a differential pressure (DP) regulator and rotameter to ensure that at all times the air pressure is slightly higher (but at the same difference) than the hydrostatic pressure. Constant difference in pressure is maintained by the DP regulator. The rest of the system is the same as that which has been described above and hence is not repeated here.
6. **Electronic level sensing:** Rise and fall in head, i.e., the change in head is basically due to rise and fall in level. Therefore, electronic level transducers working on conductance and capacitance could be deployed for this purpose. Both conductance- and capacitance-type sensors are contact-type sensors, i.e., these sensors are mounted in the channel or in the stilling chamber from the top. These sensors are connected to a measuring circuit, which is excited by one high-frequency oscillator. When there are changes in the level there will be changes in conductance (hence resistance) or capacitance of the probe connected to the electronic circuit (because the water level inside the probe changes). These changes will cause changes in the circuit current, which are sensed and sent to the transducer. Apart from these, there is also a noncontact-type ultrasonic (US) level sensor. Here the transreceiver is placed over the water surface (in the channel and/stilling chamber) at a fixed distance. The US transmitter sends the signal towards the water surface at which the ultrasound is reflected back to the transceiver. At the transreceiver the detector detects the ultrasound. The time difference between US wave transmission and reception is known as time of flight (see Chapter I Section 3.1.3, Fig. I/3.1.3-4), which is measured. With the rise and fall in level the time of flight will decrease or increase, respectively. A signal based on the time of flight is sent to the transmitter circuit. The transmitter sends these changes either as a hardwired signal 4–20 mA DC or data sent via the HART protocol or by fieldbus data for recording, data logging, and/or recording/printing.

2.2.0 Venturi Flume

The most common type of flume is the Venturi flume. Like the Venturi tube, there is one converging section, followed by a throat section, and then a divergent section. A Venturi flume is a critical-flow open-channel flume with a constricted flow, like a Venturi tube. This causes a drop in the hydraulic grade to create a critical depth. Based on the length of the throat these are called long-throated or short-throated Venturi flumes. The Parshall flume, which is discussed separately, is an example of a short-throated Venturi flume. It is used in flow measurement

of very large flow rates. A Venturi tube meter normally measures DP in millimeters of water column, whereas a Venturi flume in free-flow conditions, i.e., if the flumes are designed so as to pass the flow from a subcritical to supercritical state while passing through the flume measures, upstream pressure is in meters. However, in the case of submerged condition of flow, when the flow passes in a subcritical state through the flume, then measurement of discharge with Venturi flumes requires two measurements, one upstream (h_a) and one at the narrowest cross-section throat (h_b). To ensure the occurrence of critical depth at the throat, the flumes are usually designed in such a way as to form a hydraulic jump on the downstream side of the structure as shown in Fig. III/2.2.0-1B–D.

If C_d is the discharge coefficient and w is the throat width, then the general flow equation for a Venturi flume can be given by

$$q = \frac{2}{3} C_d \cdot w \cdot \sqrt{2g} \cdot h^{1.5} \quad \text{or} \quad q = Kh^{1.5} \tag{III/2.2.0-1}$$

The effect of the velocity approach is taken care of automatically by the primary device. Also, the Venturi flume is free from interference due to the changes in canal section from sand, etc. Normally Venturi flumes have a flat bottom, which is different from Parshall flumes where the bottom at the throat has a downward slope. The Parshall flume is the most popular and is slightly different from the Venturi flume in construction and hence is dealt with separately. Different types of Venturi flumes are discussed below.

2.2.1 DIFFERENT VENTURI FLUMES

Various kinds of Venturi flumes are described here, for this the reader is referred to the associated figures.

1. **Rectangular:** Both rectangular and trapezoidal flumes function by having a constriction at the throat, which is a typical characteristic of Venturi flumes. In addition to this there can be a raised invert (bottom) at the throat. Both these constructional features help in attending to the critical flow at the throat in a properly operating flume. In a bottom hump type of flume, the combined effects of the sidewalls and streamline vertical curvatures predominantly affect the behavior of the curvilinear flows, especially in the vicinity of the critical section where the flows exhibit three-dimensional (3D) characteristics with cross-waves [12]. A rectangular flume is shown in Fig. III/2.2.0-1B.

   These flumes are simpler to construct, and can be more easily fit into an existing channel. However, these can trap less sediment than a Parshall flume. ISO 4359 (1983, 1999) is a major standard followed for rectangular, trapezoidal flumes. In rectangular Venturi flumes, constriction is only at the side, so it is easier to construct.
2. **Trapezoidal:** Trapezoidal flumes are a little more complicated to design and construct, but provide a wide flow range with low pressure loss [13]. For free flow, the standard formula given in Eq. (III/2.2.0-1) can be used. On account of the construction there is a slight difference in the power value for h, so a trapezoidal flume is represented as

$$q = C_d \cdot h^{nf} \tag{III/2.2.0-2}$$

   (where n is determined by the proportions of the flume.)

   A trapezoidal flume actually has five sections, including the approach, convergent, throat, divergent, and exit, although the first and last sections are really not part of the flume. In a trapezoidal flume seen from the ends (end view), the throat base width is narrowest compared to the other sections. Trapezoidal flumes can offer accuracy within 5% when properly constructed (following specified tolerances) and installed. In a trapezoidal flume only free flow is used (see Fig. III/2.2.0-1D).
3. **V notch:** When the base width at the throat (w) is zero it is a v notch flume. It has similar characteristics to the V notch weir—water has

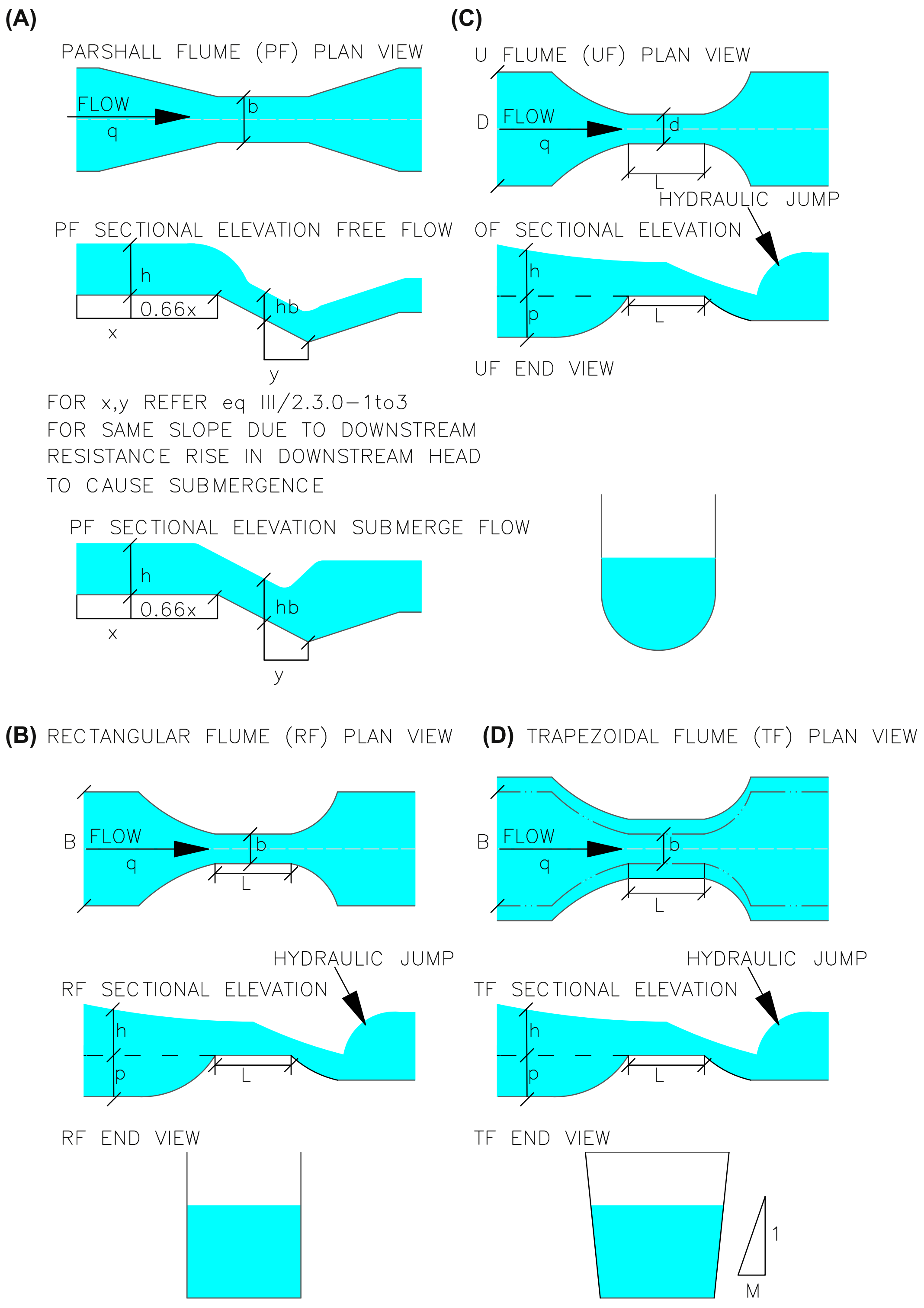


FIGURE III/2.2.0-1 Venturi flume types. (A) Parshall flume (head). (B) Rectangular flume. (C) U flume. (D) Trapezoidal flume.

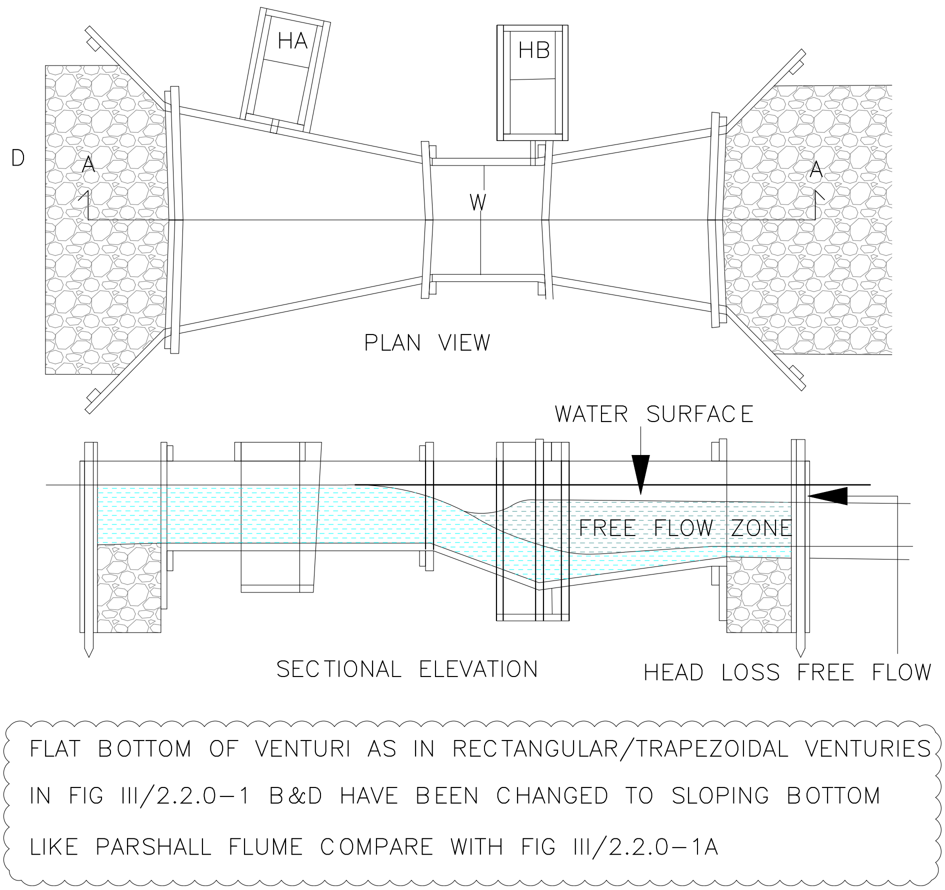


FIGURE III/2.2.0-2 Improved Venturi flume. *Adapted from R.L. Parshall, The Improved Venturi Flume, Irrigation Engineer, The Colorado Agriculture College, https://dspace.library.colostate.edu/bitstream/handle/10217/5168/COAB_3873989.pdf?sequence=1* Courtesy.

a small head, but more rapid change in head due to a change in discharge. When the depth of water is low, floating trash might lodge in the throat of the V-notch Venturi flume. As the cross-section is small, this would cause an accumulation of water in the upstream channel until the wetted cross-section at the throat is sufficient to allow the obstruction to pass.

4. **U-flume:** U-flumes are round-bottomed flumes with a raised inverted floor as shown in Fig. III/2.2.0-1C. These are similar to Palmer—Bowlus flumes that are discussed later. They have a semicircular throat and are commonly used in culverts and pipes. Critical flow is achieved by narrowing the throat or by raising the bottom of the flume at the throat. These flumes are analyzed in a way adapted for trapezoidal flumes.

2.3.0 Parshall Flume

The Parshall flume was named after its inventor, Dr. R.L. Parshall of US Conservation services. This is basically a Venturi flume with a short length of throat. In place of the flat bottom in a conventional Venturi, here the bottom is contoured, i.e., it has a stepped floor. The inlet section floor is flat. The throat has a downward slope and the divergent section has an upward slope. The Parshall flume is illustrated in two figures (Fig. I/3.1.5-1 and Fig. III/2.2.0-1A). In both the case floor slopes, and conditions at free-flow and submerged flow-conditions have been shown. Parshall flumes are fabricated locally with a variety of materials. They operate over a wide range of flows. It can be operated in both free flow and submerged flow. Like other flumes, it is a self-cleaning type and head loss is low.

As long as the downstream level does not exceed *70%* of the level measured near the upstream end, then the downstream level does not affect the upstream level measurement. In the case of free flow it is possible to determine discharge by single head/level measurement in the upstream side. However, in the case of submerged flow, head measurements in stilling chambers at the converging upstream section and head in a stilling chamber in the throat section are required. The device offers good accuracy and repeatability with moderate maintenance. It offers good rangeability of flow. The basic shape of each Parshall flume is same but not scalable. Therefore, one has to get the discharge equation for any Parshall flumes through calibration. Generalized equations are dimension-dependent. So, based on the generalized equation, the design must be developed. Then through calibration theoretical results are compared with calibration data to find the correction factor. Short discussions will now be put forward on the generalized equation for Parshall flumes under free-flow and submerged-flow conditions.

2.3.1 DESIGN AND DISCHARGE EQUATION

As stated above discharge equations are dependent on various dimensions of Parshall flume. Similarly, measurement points are also decided based on the dimensions. As shown in Fig. III/2.2.0-1A, there are two parameters x and y shown. As shown in Fig. III/2.2.0-1A the measuring positions for h and h_b have been specified in terms of x and y, where y is related to the width of throat w. The relationship is as follows

$$y = 0.05\ \text{m} \quad \text{for } b < 3.05\ \text{m}; \qquad y = 0.305\ \text{m} \quad \text{for } b \geq 3.05\ \text{m}. \tag{III/2.3.0-1}$$

Also, h_b/h depends on width in the following way

For free flow, at

$$b < 3.05\ \text{m} \quad h_b/h \leq 0.6; \qquad b \geq 3.05\ \text{m} \quad h_b/h \leq 0.8 \tag{III/2.3.0-2}$$

For submerged flow, at

$$b < 3.05\ \text{m} \quad h_b/h \geq 0.6; \qquad b > 3.05\ \text{m} \quad h_b/h > 0.8 \tag{III/2.3.0-3}$$

From the above it is clear that the throat width has a bearing on head values and hence on discharge coefficients. The generalized discharge equations are described here.

1. **Free flow discharge equation:** The study showed that a single Parshall flume can be used to measure flow for both supercritical and subcritical flow regimes for a specified range of flows, an accuracy of almost ±5%. The flow equation and the method of flow analysis are different for each type of flow [14]. Under free-flow conditions, discharge through the Parshall flume mainly depends on the upstream head which can be expressed as:

$$q = C_d\, h^n \tag{III/2.3.0-4}$$

where q = discharge through the flume; C_d = discharge coefficient which depends on width w or b (as per Fig. III/2.2.0-1A); h = upstream head measured at 2/3× the converging section from the throat as shown in Fig. III/2.2.0-1A; and n = exponent of head h. For analysis Eq. (III/2.3.0-4) can be rewritten as:

$$\log q = \log\left(C_d h^n\right) \quad \text{or} \quad \log q = \log C_d + n \cdot \log h \quad \text{or} \quad Y = A + nX \tag{III/2.3.0-5}$$

where log q = Y; log C_d = A; log h = X. From here standard programming like MATLAB can be used to determine the discharge coefficient (also represented as C_f). Standards such as ASTM D provide standard tables for these parameters. Now, to marry these standards with ASTM-D Eq. (III/2.3.0-4) we get

$$Q = KH_a^n \quad \text{(III/2.3.0-6)}$$

Here Q is discharge in m^3/s or cu·ft/s; K is flume discharge constant which varies with flume size and units; H_a is the depth at the point of measurement in meters or feet; n is the discharge exponent which depends on flume size. Table III/2.3.0-1 provides different values of C_d (K) and n for various sizes of width w (or b as per Fig. III/2.2.0-1A) as per ASTM D (in **mm**).

2. **Submerge flow equation:** This is as already mentioned for submerged flow (two head).

   Measurements are necessary for one upstream head measurement at the converging section represented by h_a (H_a) and another at the throat h_b (H_b). If the submergence ratio $S = \left(\frac{h_a(H_a)}{h_b(H_b)}\right)$, the submergence coefficient C_s, C_f is the free-flow coefficient and w the flume width, then discharge q is given by

$$q = C_s \cdot w \cdot (h_a - h_b)^{nf} \cdot \frac{1}{\{-(\log_{10} S + 0.0044)\}^{ns}} \quad \text{(III/2.3.0-7)}$$

where n_s and n_f are the free-flow exponent and submerged-flow exponent, respectively. As with free flow, here n_f/n_s or C_s/C_f are also functions of flume width w. Variations of these constants with flume size are tabulated below. Eq. (III/2.3.0-7) can also be used for transition submergence. Values of these related parameters for different width w has been presented in Table III/2.3.0-2.

It is worth noting that under free flow conditions there is more or less agreement between the results obtained using ASTMD 1941 and ISO 9826, yet in submerged conditions there may be variations in the results between the two standards. Therefore, while designing, the standard to be followed should be decided before hand.

TABLE III/2.3.0-1 Parshall Flume Free-Flow Parameter Variations in Width (mm)

Throat Width (mm)	K in Imperial Unit	K in SI Unit	Exponent n
1″ (25)	0.338	0.0479	1.55
2″ (50)	0.676	0.0959	1.55
3″ (75)	0.992	0.141	1.55
6″ (150)	2.06	0.264	1.58
9″ (225)	3.07	0.393	1.53
12″ (300)	4.0	0.624	1.522
1′6″ (450)	6	0.887	1.538
2′ (600)	8	1.135	1.55
3′ (900)	12	1.612	1.566
4′ (1200)	16	2.062	1.578
5′ (1500)	20	2.5	1.587
6′ (1800)	24	2.919	1.595
10′ (3000)	39.38	4.709	1.6
12′ (3600)	46.75	5.59	1.6
15′ (4500)	57.81	6.912	1.6
20′ (6000)	76.25	9.117	1.6
25′ (7500)	94.69	11.32	1.6
30′ (9000)	113.13	13.53	1.6
40′ (12000)	150	17.94	1.6
50′ (15000)	186	22.35	1.6

TABLE III/2.3.0-2 Parshall Flume Submerged Flow Parameter Calibration With Width (mm)

	Imperial Unit		SI Unit			
Throat Width (mm)	C_f	C_s	C_f	C_s	n_f	n_s
1″ (25)	4.06	3.59	2.38	2.10	1.55	1.000
2″ (50)	4.06	3.67	2.38	2.15	1.55	1.000
3″ (75)	3.97	3.66	2.32	2.14	1.55	1.000
6″ (150)	4.12	3.32	2.50	2.02	1.58	1.080
9″ (225)	4.09	3.35	2.34	1.91	1.53	1.060
12″ (300)	4.00	3.11	2.26	1.76	1.52	1.080
1′6″ (450)	4.00	2.95	2.32	1.71	1.54	1.115
2′ (600)	4.00	2.97	2.34	1.74	1.55	1.140
3′ (900)	4.00	2.87	2.37	1.70	1.56	1.160
4′ (1200)	4.00	2.78	2.40	1.66	1.57	1.185
5′ (1500)	4.00	2.71	2.43	1.65	1.58	1.205
6′ (1800)	4.00	2.64	2.46	1.62	1.59	1.230
7′ (2100)	4.00	2.59	2.49	1.61	1.60	1.250
8′ (2400)	4.00	2.55	2.49	1.59	1.60	1.260
10′ (3000)	4.01	2.48	2.47	1.52	1.59	1.275
12′ (3600)	3.96	2.45	2.43	1.50	1.59	1.275

Courtesy: Universal Equation for Prashall Flume Submergence; Open Channel Flow. http://www.openchannelflow.com/blog/universal-equation-parshall-flume-submergence.

2.3.2 PARSHALL FLUME INSTALLATION DISCUSSIONS

Proper functioning of the Parshall flume is highly dependent on the hydraulic design. Therefore, it needs special attention from specialists. A few pertinent pitfalls are discussed here. From a location point of view, the place where the Parshall flume is to be installed should have smooth streaming in front of the flume—free of whirls and undulation, etc., so as to ensure a balanced speed distribution profile.

1. **Dimensional issues:** For these reasons, the flume should be installed at a safe distance from the end of a curve (at least 12 w), or for the drop wall at least 30 W (depends on the depth and on the shape of floor) [16]. For channels wider than the Parshall flume, constriction in the inlet should be as high as 45 degrees to the axis and the bottom down to 15 degrees.
2. **Free-flow installation:** The majority of installations demand Parshall flume operation under free-flow conditions. The following are some important issues for free-flow conditions:
   - Establishment of the maximum flow rate to be measured.
   - To find the high water line on the canal bank where the flume is to be installed.
   - Determination of the maximum depth of flow.
   - From the discharge table select the proper depth of water corresponding to maximum discharge capacity.

- Place the bottom of the flume at a suitable depth, so that it does not exceed the transition submergence.

3. **Submerged-flow installation:** Under certain conditions it is necessary to operate under submerged-flow conditions. There is one advantage to submerged flow in that there will be less head loss through the flume, hence canal banks upstream from the flume do not have to be raised in order to maintain the same maximum flow capacity [17]. Also, quicker drainage is possible. The major issues related to submerged flow include but are not limited to the following.
   - The first three points mentioned above in Subsection 2.3.2.2 are also applicable here—hence they are not repeated.
   - Taking into account the amount of freeboard in the canal at maximum discharge and maximum flow depth, determine how much higher the water surface can be raised in the canal above the location for the flume.
   - Select the required size of flume from the submerged flow calibration curves by trial and error. With the floor of the flume placed at nearly the same elevation as the bottom of the canal, the maximum depth of flow can be used as H_b' and the amount that the water surface in the canal can still be raised, can be used as $H_a - H_b$. With this information, the submergence, $S = H_b/H_a$, can be computed. Knowing $H_a - H_b$ and H_b/H_a allows the size of the flume to be selected from the submerged-flow calibration curves.

2.4.0 H Flume

Unlike the U flume, this is not named on account of its shape but is so named as it is the eighth in the series (as the letter H is the eighth letter in the English alphabet) of flumes investigated. It was developed by US forestry services for portable measurement of water. It may be considered as a transition between a flume and weir (as shown in Fig. III/2.4.0-1).

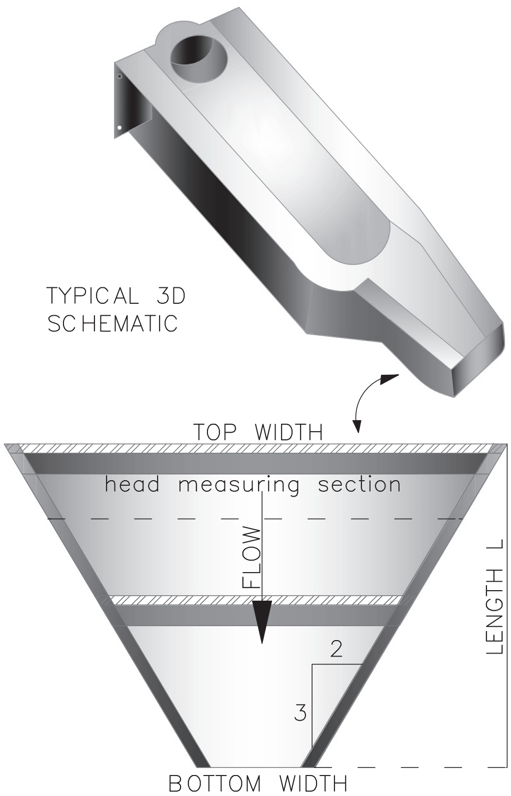


FIGURE III/2.4.0-1 H flume.

As indicated above, the V notch has high sensitivity. This is combined with the flat floor of a flume. Because of its construction (as is clear from the figure) it also possesses the property of self cleaning, normally found in flumes. Characteristic features of H flumes include:

1. Wider range of flow than other flumes;
2. Used as a portable water measurement system;
3. Lower sensitivity to measure higher flow;
4. Well suited for clearing sediments and smaller debris but not suitable for sewerage/sanitary applications.

Aluminum, galvanized steel, and stainless steel are the most commonly used materials in the construction of H flumes. The measuring point in an H flume is selected during development. The measurement point is very important in H flumes as it is sensitive to slight errors. Like a trapezoidal flume it is used in free flow. As H flumes require a nonimpeded discharge, they cannot be used in submerged-flow applications.

2.5.0 Cutthroat Flume

As the name suggests, there is no throat section but there are convergent and divergent sections. Therefore a cutthroat flume can be conceived of as a rectangular flume with a flat bottom and throat length equal to zero. These were developed in the mid-1960s and one is depicted in Fig. III/2.5.0-1. In this connection, Fig. I/3.1.5-2B may be referred to as a Khafaji flume. On account of the flat-bottom design it is easier to construct and place on a channel bed or concrete channel.

Eq. (III/2.5.0-1). Here the suffix "f" represents the free-flow condition and w represents the discharge coefficient at free-flow conditions and throat (zero length) width, respectively. The upstream head is represented by h.

$$q_f = C_{df} \cdot w \cdot h^{nf} \qquad \text{(III/2.5.0-1)}$$

The generalized equation of discharge through a cutthroat flume under submerged-flow conditions is given by Eq. (III/2.5.0-2), where h_u and h_d represent upstream and downstream heads

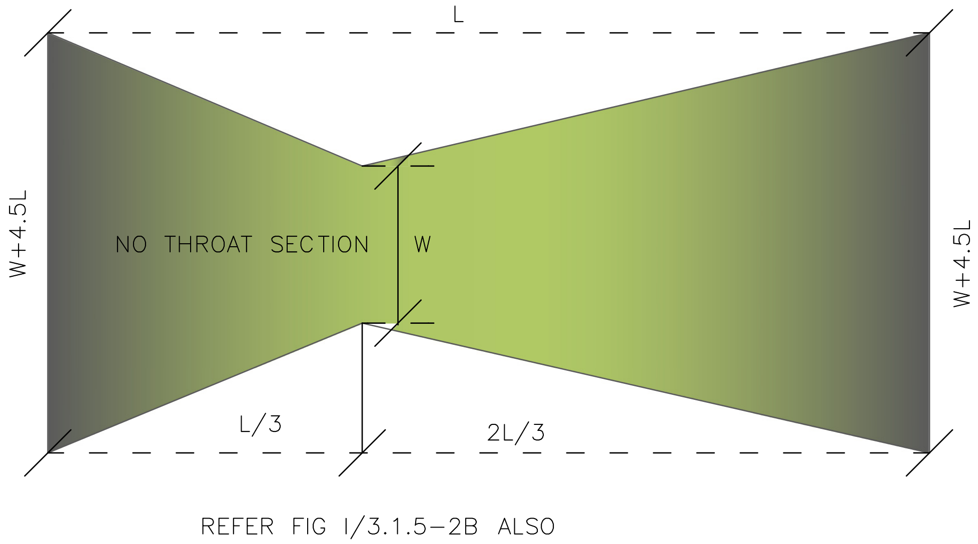


FIGURE III/2.5.0-1 Plan view of a typical cutthroat flume.

A few characteristic features of cutthroat flumes are worth noting. These include:

1. Cut throat flumes have a fixed dimension ratio;
2. Commonly used lengths of cutthroat flumes ranges between 500 and 2500 mm;
3. Normally the ratio of upstream head to length is 0.33;
4. Popular w/L ratios are 1/9, 2/9, 1/3, 4/9;
5. Cutthroat flumes can be used for both free and submerged flows;
6. For submerged flow a downstream head is measured in the divergent section;
7. Cutthroat flumes are suitable for both free- and submerged-flow measurements.

The general discharge equation for a cutthroat flume in a free-flow condition is given by measured, w is the throat width, $S = h_d/h_u$; C_{ds} is the submerged-flow coefficient, and the suffices f and s stand for free and submerged flow, respectively.

$$\text{Submerge flow: } q_s = C_{ds}(h_u - h_d)^{nf} \cdot \frac{1}{(-\log S)^{ns}} \qquad \text{(III/2.5.0-2)}$$

Eq. (III/2.5.0-2) may be compared with Eq. (III/2.3.0-7) to illustrate the similarity.

2.6.0 Palmer–Bowlus

The Palmer–Bowlus flume, developed in the USA in 1936 for use in wastewater treatment, was named after its inventors, Messrs. Palmer and Bowlus [13]. Palmer–Bowlus flumes are also

used for industrial waste flow applications. Apart from these applications, they finds applications in flow measurements in spring discharge, well pumping tests, and wastewater treatment plants. The Palmer—Bowlus flume shown in Fig. I/3.1.5-2A has inherent advantages of rounded bottoms and relatively small size. On account of these advantages it has easier installation in sewer manholes, pipe inverts, etc. However, on account of the raised throat there is a chance of silt deposition in the primary element. This flume is scaled as multiples and submultiples of throat width (w). The head sensitivity to discharge is low and can cover a wide range of 3500:0.3 (L/s). Palmer—Bowlus flumes have a U-shaped cross-section to minimize the transition of flow. The throat of a Palmer—Bowlus flume is created by a raised trapezoidal ramp section. As the floor rises the side walls contract. This combined action forces the water to accelerate in the throat section. The elevation of inlet and outlet of the flume are at the same elevation. Accessories for Palmer—Bowlus flumes include: piping end connection; floor mount; flow conditioner; sample, etc. There are a number of styles and variations available for Palmer—Bowlus flumes, including [18]:

1. Insert style;
2. Short section with integral approach;
3. Permanent with integral approach;
4. Permanent style;
5. Cutback style.

This ends the discussions on flumes and we now turn our attention to the other primary device, the weir.

3.0.0 WEIRS

Like flumes, weirs are also an obstruction across an open channel over which water flows, often through a specially shaped opening or notch. A weir is one of the most simple, economic, and common primary devices for open-channel flow measurement. Weirs are only applicable to open-channel flows and for water at ordinary temperatures of about 4—30°C; in Chapter I the broad classifications are presented. A more precise classification of weirs is presented here. These are:

- Triangular/V notch with varied angle (30—90 degrees);
- Rectangular (suppressed or contracted);
- Trapezoidal or Cipoletti;
- Broad-crested;
- Sutro weir;
- Overshot gate.

Various terms associated with weirs are shown in Fig. I/3.1.5-3 and discussed in Subsection 3.1.5.2 of Chapter I. As discussed in Subsection 3.1.5.2 of Chapter I, there is a requirement weir ventilation, if the downstream water rises to any point, when the nappe is not properly ventilated, then it will have a direct effect on the accuracy and stability of measurements. As discussed earlier, the discharges are measured as the depth of the water in the weir pool, i.e., the water body upstream of the weir. The head is measured as function of the difference in depth from the surface of the water to the elevation of the weir crest. The point of measurement is located approximately little more than 30 times the maximum anticipated head (depth). Any distance closer than this may have a downstream effect, already discussed in the previous section. The stilling basin ahead of the weir should be large enough to limit the velocity to 0.01 m/s (0.33 ft/s) [10]. The width and depth immediately ahead of the weir should be sufficient to avoid/eliminate the wall effect of the bottom and sides.

3.1.0 Weir General Discussion

Weirs are broadly classified as sharp-crested and broad-crested. Within sharp-crested types, there are triangular/V-notch, Cipoletti/trapezoidal and rectangular types. There are two different types of rectangular weir, i.e., suppressed ($L = B$) and contracted ($L < B$). In all these types, the relationship between discharge (q) and upstream level (h) is given by the general equation $q \propto h^m$, where m is a constant number.

However, there is an exception to this relationship in Sutro weirs, where discharge (q) is related to upstream level (h) in a linear relationship. All are depicted in Fig. III/3.1.0-1.

There is another type called the overshot gate; this will be discussed after submerged flow over the weir is discussed. The head measurement is an important aspect because from this only, discharge for any weir can be computed.

1. **Head measurement:** As in flumes, head measurement in weirs is also extremely important. As, this is quite similar to what has been discussed in Sections 2.1.6 and 2.1.7, the details are not repeated here. Depending on applicability these will be utilized for weir applications, see especially Sections 2.1.6.4 and 2.1.7.

2. **Common conditions and requirements for weirs:** Some conditions and requirements common to all sharp-crested weirs are summarized below:
   - The upstream face of the weir and bulkhead crest should be smooth upright and normal to the flow axis.
   - All weir opening edges should be in one plane, with corners at specified angles. All weir plates should have the same thickness for the entire boundary and the plate edges should be chamfered at an angle of at least 45 degrees (60 degrees as shown in Fig. III/3.1.0-1B).
   - The nappe should touch only the upstream faces of the crest and side plates. The

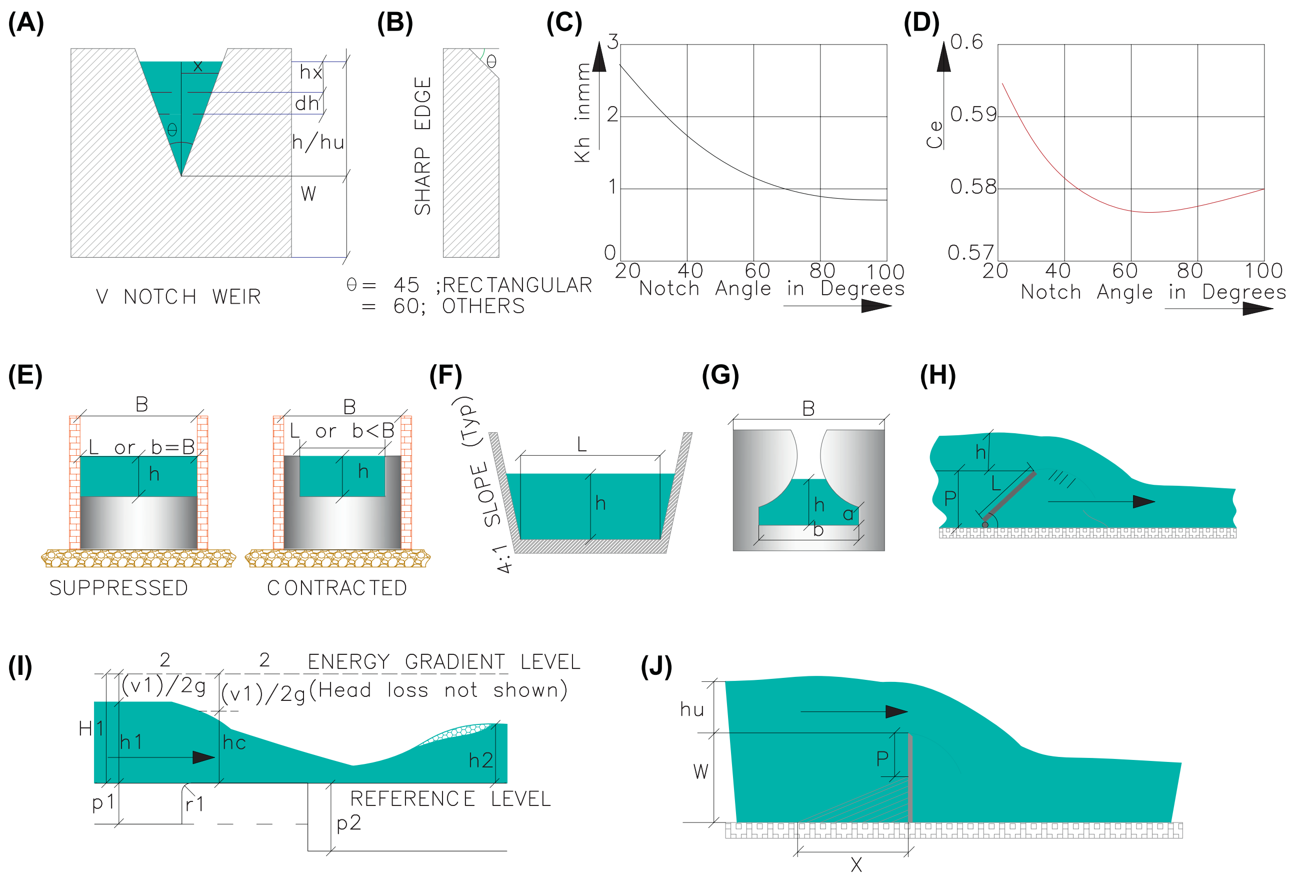


FIGURE III/3.1.0-1 Weir types and effect. (A) Calculation basis. (B) Sharp edge. (C) K_h versus notch angle. (D) C_e versus notch angle. (E) Rectangular weir. (F) Cipoletti weir. (G) Sutro weir. (H) Overshot gate. (I) Broad-crested weir. (J) Siltation. *(H and J) Courtesy of G.P. Markkley, Weirs for Flow Measurement, Lecture 8; Bie 5300/6300 Lectures. http://ocw.usu.edu/Biological_and_Irrigation_Engineering/Irrigation___Conveyance_Control_Systems/6300__Weirs_for_Flow_Measurement_Lecture_Notes_1.pdf.*

upstream edges of the weir opening plates must be straight and sharp.

- The maximum downstream water surface level should normally be at least 5 cm below the crest elevation.
- The measuring head on the weir is the difference in elevation between the crest and the water surface at a point located upstream at a distance of at least four times the maximum head on the crest from the weir.
- Keep the approach to the weir crest free of sediment deposits.

Before we move on to other discussions let us analyze and find the mathematical equations for discharge in weirs.

3.1.1 WEIR CALCULATION DETAILS

From previous discussions it is clear that the discharge through a weir is measured and computed by measuring the difference in upstream water level, h. Therefore it is necessary to develop an equation for discharge q with respect to h (mostly in the form of $q = Ch^m$, i.e., $q \propto h^m$ and C is constant). In this section, the calculations and equations are put forward.

1. **Calculation basis:** The flow equations for various weirs can be established by selecting a small section of water passing through the weir. This has been shown in Fig. III/3.1.0-1 (leftmost figure A) where a tiny water section with depth dh has been chosen. If 2x is the width of this section as shown in the figure under reference, then, $dA = 2xdh$. Then, as per figure, $\tan\theta/2 = x/h_u - h_x$; therefore, if area is multiplied by velocity one gets the discharge. Now the velocity head can be expressed in terms of level head h as $v = \sqrt{2gh}$. Therefore, by inserting values one gets $dq = C_d \cdot \sqrt{2gh} \cdot dA$; where C_d is the discharge coefficient. On integrating,

$$q = C_d 2\sqrt{2g}\tan\theta/2 \int_0^{h_u} (h_u - h_x)\sqrt{h_x}\,dh \qquad \text{(III/3.1.1-1)}$$

or,

$$q = 0.754 C_d \sqrt{g}\tan\theta/2h_u^{5/2} \qquad \text{(III/3.1.1-2)}$$

For a given angle (say $\theta = 90$; $\tan\theta/2 = 1$) $\tan\theta/2$ is known, and C_d is constant. So, with all constants together, Eq. (III/3.1.1-2) reduces to

$$q = Ch^{5/2} \qquad \text{(III/3.1.1-3)}$$

hence, $q \propto h^m$, as indicated in the initial discussions.

2. **Flow equations for various weir types:** Having established the q−h relationship, equations for various types of weirs are listed in Table III/3.1.1-1. Prior to going to the table, the following details should be noted. In this table the first four categories are sharp-crested. The meaning of sharp-crested is illustrated in Fig. III/3.1.0-1B. As mentioned, the fifth in the table is the broad-crested type. This has a raised horizontal sill of sufficient length in the flow direction to effect an horizontal surface. In contrast to the nonlinear relation between head and discharge, in a Sutro weir (the final entry in the table) q is proportional to head in the upstream. For various units related to sharp crest weirs, the following point may be noted: *Unless otherwise stated q = liters/sec; L = crest length; h, head; in metric system L or h in cm; q = liters/sec and imperial system L or h in feet; q = cft/s/sec. The values of constants in the imperial system are indicated in brackets.*

3. **Shen equation:** Apart from standard weirs like the v notch, rectangular, and Cipoletti there are some modified designs for calibrations in the laboratory. The Shen equation is one of these as it is a modified form of the triangular/V notch weir. The Shen equation should be read in conjunction with Fig. III/3.1.0-1A and the equation for V notch in Table III/3.1.1-1. The Shen equation is:

$$q = \frac{8}{15}\sqrt{2g}C_e \tan\left(\frac{\theta}{2}\right)h_e^{5/2} \qquad \text{(III/3.1.1-11)}$$

TABLE III/3.1.1-1 Discharge Equation of Various Weir

Weir Type	Discharge Equation	Equation No.	Figure No.	Remarks
Rectangular	$q = C \cdot L \text{ (or b)} \cdot h^{3/2}$ $C = 0.0184\ (3.33)$	(III/3.1.1-4)	III/3.1.0-1E	Suppressed (L or b = B)
Rectangular	$q = C \cdot (L^* - 0.2h) \cdot h^{3/2}$ $C = 0.0184\ (3.33)$	(III/3.1.1-5)	III/3.1.0-1E	Contracted (L or b = <B) *L also represented by b in standards.
Triangular/ V notch	$q = C \cdot \tan\theta/2 \cdot h^{5/2}$	(III/3.1.1-6)	III/3.1.0-1A	C = 0.0138 (2.48)
Cipoletti/ trapezoidal	$q = CLh^{3/2}$	(III/3.1.1-7)	III/3.1.0-1F	C = 0.0186 (3.367) when L/H in cm; q in L/s
Broad-crested*	$Q = C_d \cdot C_v \frac{2}{3} b \sqrt{\frac{2g}{3}} h^{3/2}$	(III/3.1.1-8)	III/3.1.0-1I	Coefficients: C_d discharge C_v: approach velocity
Sutro	$q = C_d \cdot b \cdot \sqrt{ga}\left(h - \frac{a}{3}\right)$	(III/3.1.1-9)	III/3.1.0-1G	C_d discharge coefficient

*Similarly for narrow-crested with L and h in meters and discharge m^3/s discharge: $q = \frac{2}{3} C_d \cdot L \cdot \sqrt{2g} h^{3/2}$ (III/3.1.1-10).

where effective head

$$h_e = h(h_u) + K_h \qquad \text{(III/3.1.1-12)}$$

Variations of K_h and C_e with respect to variation of the notch angle are depicted in Fig. III/3.1.0-1C and D.

3.1.2 SUBMERGED FLOW IN A WEIR

In the case of closed conduits, flow regimes have been noted. In the case of open-channel flow also there are two regimes: free (critical) flow and submerged (subcritical) flow. For free flow, critical depth normally occurs near the crest of the weir and for measurement of the same the depth upstream from the point of critical depth is monitored. When the downstream depth is raised sufficiently, the flow depth at the crest becomes greater than the critical depth, and submerged flow conditions exist. For submerged flow, a change in the downstream depth also affects the upstream depth and a rating for the weir requires that two flow depths be measured. The flow condition at which the regime changes from free flow to submerged flow is a transition state or the transition submergence [19]. According to Prof. J.R. Villemonte "submerged weirs conserve elevation and should have wide application in design of gravity systems where savings in head loss mean savings in construction costs" [20]. As per the hydraulic experiment carried out, he divided flow into two parts, namely, free flow over the weir with head as the difference between the upstream (h_u) and downstream (h_d) levels and submerged orifice-like flow as the function of difference between upstream and downstream levels as indicated in Fig. III/3.1.2-1. Therefore,

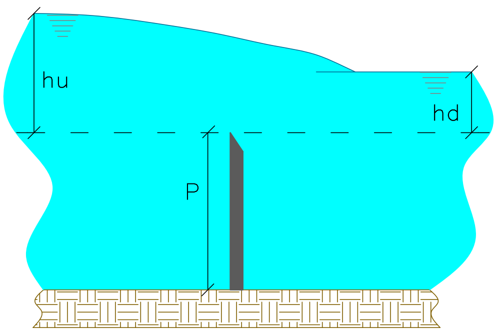


FIGURE III/3.1.2-1 Submerged weir.

submerged flow is a function of free flow and heads h_u and h_d as per the following equation:

$$q_s = q_f\left[1-\left(\frac{h_d}{h_u}\right)^n\right]^{0.385} \quad \text{or} \quad K_s q_f$$

(III/3.1.2-1)

$h_d \le 0$, $K_s = 1.0$; free flow, $h_d > h_u$ back flow; $q_s = 0$ at $h_d = h_u$; $n = 1.5/2.5$. There is another approach to analyzing submerged flow over weirs by Robinson (1964) for measuring a trapezoidal flume as the ratio of actual discharge and critical flow.

3.1.3 OVERSHOT GATES (SUBMERGED FLOW)

This is basically a part of submerged flow measurement. Overshot gates, also known as leaf gates, are moveable weirs developed mainly for upstream-level controls in open-channel flows. Here a short description and features of these are discussed.

1. **Description:** An overshot gate consists of a gate leaf, hinge, and hoist mechanism. These weirs are hinged at the base at the bottom, on the channel floor recessed portion, so that it can lie flat on the channel floor in a wide-open condition. With the help of steel cables on either side of the gate leaf, it can be opened at an adjustable angle setting required. The steel cable is attached to a shaft which can be rotated by a motor to adjust the angle. A typical overshot gate is shown in Fig. III/3.1.0-1H. At lower angles it behaves like free overfall [21]. The overshot gate can be set to any position between 0 and 60 degrees (0 degrees being flat or open), therefore establishing upstream level control (Armtec company, Canada—manufacturer of overshot gates). The following generalized equation for overshot gates was developed by Wahlin and Replogle in 1996:

$$q = K_s C_a C_e \frac{2\sqrt{2g}}{3} G_w h_e^{3/2} \qquad \text{(III/3.1.3-1)}$$

where h_e is given in Eq. (III/3.1.1-12), K_h is very small ($=1 \times 10^{-3}$ in metric system)—in most cases insignificant. G_w represents the gate width. C_e and C_a are functions of gate vertical height (p) angle setting, respectively. K_s is the submerged flow coefficient defined by Villamonte (Eq. III/3.1.2-1). In the above equation h is measured in meters (ft) to represent flow in m^3/s (cu·ft/s).

2. **Features of overshot gates:** The following are major features of an overshot gate.
   - *Intuitive control:* Different upstream water levels are achieved with gate adjustments for a given flow in amount and direction. Also, it can provide precise control, with minimum gate movement.
   - *Safety:* Surge and debris pass over and go downstream.

3.1.4 SILTATION IN WEIRS

As discussed in Subsection 1.0.3.5, there is the possibility of error in flow measurements on account of sedimentation load. In many services there are undergates to pass or flush out upstream sediments. On account of sediment there can be an increase in discharge. As shown in Fig. III/3.1.0-1J there is an apparent decrease in the height of the weir. With sediment the weir height is P and height is W. If there is siltation, the distance from the weir in the upstream side is X and the increase in discharge can be calculated using Table III/3.1.4-1 [21].

TABLE III/3.1.4-1 Increase in Discharge in Percentage (%) [21]

Apparent Weir Height: Actual Weir Height Ratio (P/W)	Siltation Length/Weir Height X/W					
	0	0.5	1.0	1.5	2.0	2.5
0.00	0	10	13	15	16	16
0.25	0	5	8	10	10	10
0.5	0	3	4	5	6	6
0.75	0	1	2	2	3	3
1.0	0	0	0	0	0	0

3.1.5 WEIR INTERNATIONAL STANDARDS

Listed below are a few international standards for design and construction for flow measurements with weirs.

1. ISO: ISO 1438, 3846, 3847, 4360, 4362, 4374, 4377, 8333, and 9827;
2. ASTM D 5242, 5614, 5640, and 5716;
3. BS 3680-P4A/P4B/P4E/P4I/4F, and 4377;
4. DIN:19558;
5. GOST R51657;
6. SAA:AS:3778.4. 1−6.

We now look into the details of different types of weirs.

3.1.6 WEIR ADVANTAGES AND DISADVANTAGES

While selecting the primary element it is necessary to note the advantages and disadvantages of each primary element.

1. **Advantages of weirs include the following:**
   - Simplest low-cost device for open-channel flow measurement;
   - Easy installation;
   - Free-flow equation, especially for V notch weir, so that field correction is possible for incorrectly constructed weirs, i.e., tailor making for specific flow;
   - Usable in over-the-ground flow;
   - Wide range of flow applications.
2. **Disadvantages:** The following are a few limitations of open-channel flow measurement by weirs:
   - Weirs normally offer lower accuracy;
   - Minimum head (0−0.06 m even 1.5 m) is necessary to ensure that the nappe springs clear of the weir crest;
   - Downstream the water level should be at least 300−400 mm lower than the crest to ensure ventilation of the weir;
   - Upstream distance is important for flow measurement as upstream disturbance affects the flow measurement. The point of measurement should be at least four times the maximum head, so a stilling chamber may be required.

3.1.7 HEAD MEASUREMENT

As in flumes, head measurement in weirs is also extremely important and suitable care should be taken in ensuring its accuracy. However, as this is quite similar to what has been discussed in Sections 2.1.6 and 2.1.7, the details are not repeated here. Refer to these sections for weir applications, especially Sections 2.1.6.4 and 2.1.7.

3.1.8 COMMON CONDITIONS AND REQUIREMENTS FOR WEIRS

Some conditions and requirements common to all sharp-crested weirs are summarized below:

1. The upstream face of the weir and bulkhead crest should be smooth upright and normal to the flow axis.
2. All weir opening edges should be in one plane, with corners at specified angles. All weir plates should have the same thickness for the entire boundary and the plate edges should be chamfered at an angle of at least 45 degrees (60 degrees as shown in Fig. III/3.1.0-1B).
3. The nappe should touch only the upstream faces of the crest and side plates. The upstream edges of the weir opening plates must be straight and sharp.
4. Maximum downstream water surface level should normally be at least 5 cm below the crest elevation.
5. The measuring head on the weir is the difference in elevation between the crest and the water surface at a point located upstream at a distance of at least four times the maximum head on the crest from the weir.
6. Keep the approach to the weir crest free of sediment deposits.

3.2.0 V-Notch Weir Details

Weirs are used for small and medium-sized water flows on small slopes. Normally these are applied at a flow range of 2 to slightly higher than 100 L/s. A span ratio of 100:1 is suitable for weirs. As already stated, for free flow, proper ventilation is necessary. A description of measuring weirs with sharp metering edges has already been given in Chapter I and previous sections in this chapter. It has been found that there are a few variations in flow equations.

1. **Rehbock–Thomson equation:** A typical V notch with notch angle θ has been depicted in Fig. III/3.1.0-1A and Fig. I/3.1.5-3. As per Rehbock and Thomson, the generalized flow equation given in Table III/3.1.1-1 is slightly modified and can be written as

$$q = \frac{8}{15}\mu \tan\frac{\theta}{2}\sqrt{g}h^{5/2} \qquad \text{(III/3.2.0-1)}$$

When h is plotted against the discharge coefficient a family of curves has been found for different values of the h/W ratio. This has been shown in Fig. III/3.2.0-1. From the curve it can be noted that for quite good variation of h, the discharge coefficient μ does not change much. However, for a h/W ratio change, the curve profile does not change much but is shifted appreciably in the value of μ. In the above equation the discharge coefficient is a

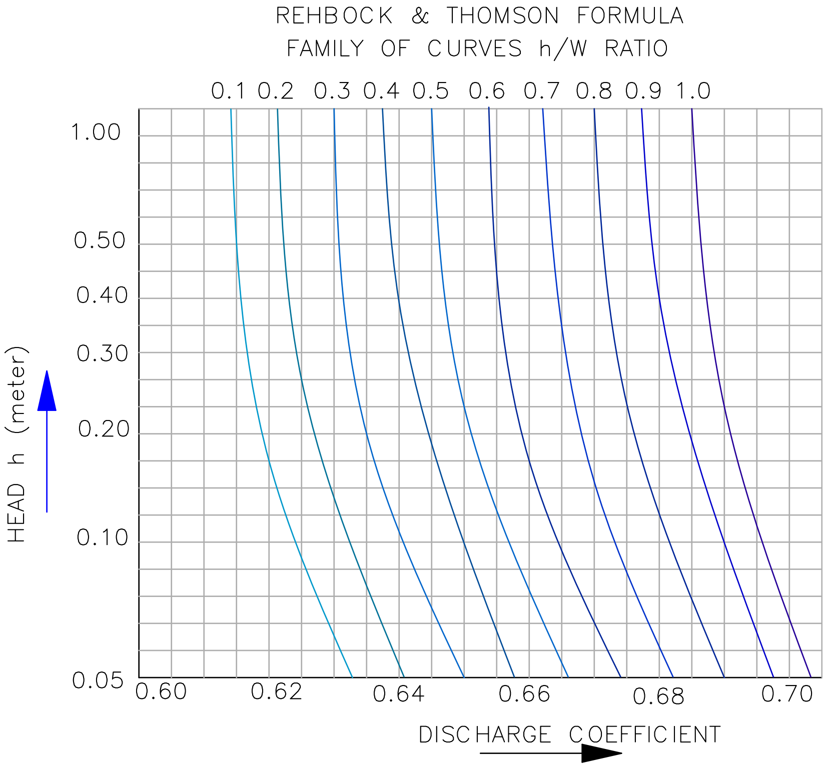


FIGURE III/3.2.0-1 V notch discharge coefficient. *Based on F. Frenzel, H. Grothey, C. Habersetzer, M. Hiatt, W. Hogrefe, M. Kirchner, G. Lütkepohl, W. Marchewka, U. Mecke, M. Ohm, F. Otto, K-H. Rackebrandt, D. Sievert, A. Thöne, H-J. Wegener, F. Buhl, C. Koch, Deppe, E. Horlebein, A. Schüssler, U. Pohl, B. Jung, H. Lawrence, F. Lohrengel, G. Rasche, S. Pagano, A. Kaiser, T. Mutongo, Industrial Flow Measurement Basics and Practice, ABB Automation Products GmbH. http://nfogm.no/wp-content/uploads/2015/04/Industrial-Flow-Measurement_Basics-and-Practice.pdf. Courtesy: ABB.*

function of the ratio between h and W. Here h and W represent the hydraulic head and W is the height of the weir as shown in Fig. III/3.2.0-1A.

2. **Kindsvater and Carter equation:** Kindsvater and Carter (1957) proposed the following practical form of this equation:

$$q = C_e \cdot \frac{8}{15}\sqrt{g}\tan\frac{\theta}{2}\cdot h_e^{5/2} \qquad \text{(III/3.2.0-2)}$$

   Eq. (III/3.2.0-2) may be compared with the Shen (1981) equation, Eq. (III/3.1.1-11). Here h_e is defined in Eq. (III/3.1.1-12). Variations of C_e and K_h with notch angle have been shown in Fig. III/3.1.0-1 C and D.
3. **Shen equation:** Refer to Subsection 3.1.1.3.
4. **Bos (1976) proposed some practical design limits as follows:** Head h to hydraulic perimeter (P) ratio, i.e., $h/p \leq 1.2$; $P > 0.1$ m; $h/B \leq 0.4$; $B \geq 0/6$ m; θ range: 25–100 degrees. For nappe aeration, the downstream level should be at least 5 cm below the crest.
5. **Advantages and disadvantages:** V notch weirs are especially suitable for low flow measurement and are simple in their operation. Higher pressure losses and lower accuracy (∼2%) goes against it.

3.3.0 Rectangular Weirs

Rectangular weirs also work on the basic principle of measuring upstream water depth, which is related to the discharge as shown in Figs. I/3.1.5-3 and III/3.1.0-1E. There are two types of rectangular weir, namely, *suppressed* rectangular weirs and *contracted* rectangular weirs. Referring to Fig. III/3.1.0-1E, it can be seen that there are two parameters, channel width B and notch width L or b. For suppressed rectangular weirs, L or b = B, whereas for contracted weirs L or b < B. *In standards* L *is also represented as* b, *so both symbols are used*. Therefore, in subsequent discussions to keep the equation the same as the original, b has been used in place of L. A generalized equation for discharge in rectangular weirs has been listed in Table III/3.1.1-1. As per standard, for contracted rectangular weir B-b (or L) should be greater than the maximum expected head h_{max}. Like a V-notch weir, Kindsvater-Carter (1959) also carried out an experiment to develop a practical equation for rectangular weirs. Although the equation is slightly different from that in the standard it is recognized as the most practical equation with an accuracy better than or equal to the standard equation. ISO (1980), ASTM (1993), and USBR (1993) all recommend using the Kindsvater–Carter method for all rectangular weirs [23]. The Kindsvater–Carter equation is:

$$q = C_e \cdot \frac{2}{3}\sqrt{2g}(b + K_b)(h + K_h)^{3/2} \qquad \text{(III/3.3.0-1)}$$

where q = discharge m^3/s; C_e is the charge coefficient; b the notch width; h the head (both are in meters); g K_b and K_h are the viscosity effect surface tension in meters; the sum $h + K_h$ is the effective head h_e (as in V notch). $K_h = 0.001$ m, so, $h_e = (h + 0.001)$ m. The sum $b + K_b$ is the "effective width," and C_e is a function of b/B and h/P, and K_b is a function of b (or L)/B. The discharge coefficient C_e is connected to the ratio of head and hydraulic perimeter, P, i.e., with h/P by Eq. (III/3.3.0-2). K_1 and K_2 are two constants related to the b/B ratio.

$$K_1 + K_2(h/P) \qquad \text{(III/3.3.0-2)}$$

Variation of K_1 with b(or L)/B has been shown in Fig. III/3.3.0-1A. Variation of K_2 and K_b has been described in Table III/3.3.0-1. As stated earlier, C_e is a function of both h/P and b/B, so from a family of curves shown in Fig. III/3.3.0-1B, the value of C_e for the particular application needs to be obtained.

Bos (1976) proposed some practical design limits; these are: $h \geq 0.03$ m; $h/P \geq 2$ (<2.5) m $P \geq 0.1$ m; $b \geq 0.15$ (1–10) m; for aeration of a nappe, the downstream level should be at least 5 cm below the crest.

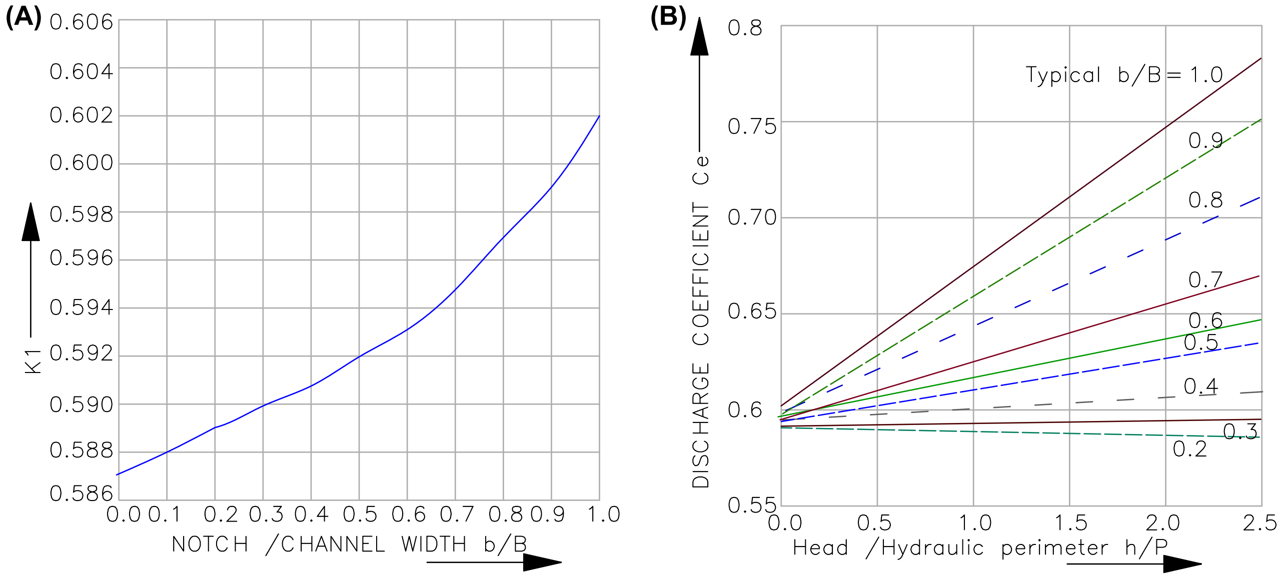


FIGURE III/3.3.0-1 Rectangular weir parameter. (A) Variation of K_1 with b/B ratio. (B) Variation of C_e with b/B ratio.

TABLE III/3.3.0-1 Some Coefficients of Rectangular Weirs

b/B Ratio	Value of K_2	Value of K_b	b/B Ratio	Value of K_2	Value of K_b
0	−0.0023	0.0024	**0.6**	0.018	0.0037
0.1	−0.0021	0.0024	**0.7**	0.030	0.0041
0.2	−0.0018	0.0024	**0.8**	0.045	0.0043
0.3	0.0020	0.0025	**0.9**	0.064	0.0037
0.4	0.0058	0.0027	**1.0**	0.075	0.0009
0.5	0.011	0.0030	*L is same as b; For K_1 refer Fig. III/3.3.0-1A.*		

3.4.0 Trapezoidal or Cipoletti

Commonly used trapezoidal or Cipoletti weirs have their origin way back in 1894. This type of weir is between a rectangular and V notch weir, because it could be conceived of as being a contracted rectangular weir with notch ends that are not vertical but instead inclined, as shown in Fig. III/3.1.0-1F. The mathematical end corrections are not necessary, hence the equation is a simplified one. Side slopes of the notch are 4:1, i.e., 4 units vertical to 1 unit horizontal, i.e., tan 14°. The generalized discharge equation for this weir has been given in Table III/3.1.1-1 (Eq. III/3.1.1-7). Like other weirs there is also a practical equation by Addison (1949). This equation is basically in the same form as has been given in Table III/3.1.1-1; the Addison discharge equation is:

$$q = 0.4158\sqrt{2g}\cdot L\cdot h^{3/2} = 1.86\cdot L\cdot h^{3/2} \quad \text{(III/3.4.0-1)}$$

where, L = crest width; h = head, and both are measured in meters, and discharge q is in m^3/s. Normally L is selected for at least 3 h (preferably 4 h or longer) for better performance.

3.5.0 Broad-Crested

So far discussions have been presented on sharp-crested weirs. Broad-crested weirs are another means to measure open-channel flow. Broad-crested weirs possess characteristics of both flumes and weirs as they have a convergent inlet section, throat, and divergent outlet. In another way they are unique, because they can be calibrated as a submerged system and can also be used for free-flow measurement. They have one crest (sill) of sufficient length, during free-flow measurement critical flow will occur over the sill and discharge will be related to the upstream head. They have transition submergence characteristics and during free-flow measurement there will be a lower increase in the upstream head.

3.5.1 FEATURES OF BROAD-CRESTED WEIRS

A few pertinent features of broad-crested weirs are listed below, including their advantages and disadvantages:

1. **Advantages:** The following are a few advantages:
   - Simple in design and construction and less expensive;
   - Low head loss and it is possible to develop an existing channel with a flat slope;
   - Debris flows over the structure with no clogging;
   - It is not necessary to use a standard structure or to rely on laboratory data;
   - Theoretical calibration with a postconstruction dimension is possible;
   - Accuracy of 2% is possible.
2. **Disadvantages:** There are some limitations to the system, including:
   - In water supplies with sediments there will be the possibility of deposition;
   - Upstream water depth will be higher;
   - Possibility of flow capacity of the channel.

3.5.2 DESCRIPTION OF BROAD-CRESTED WEIRS

The broad-crested weir has a raised horizontal crest (sill) of sufficient length in the flow direction to having a horizontal surface and hydrostatic pressure distribution as shown in Figs. III/3.5.0-1 and III/3.1.0-1I. Neglecting any energy losses, the discharge equation should be as given in Eq. (III/3.1.1-8) in Table III/3.1.1-1. In the above equation C_d is an empirically determined

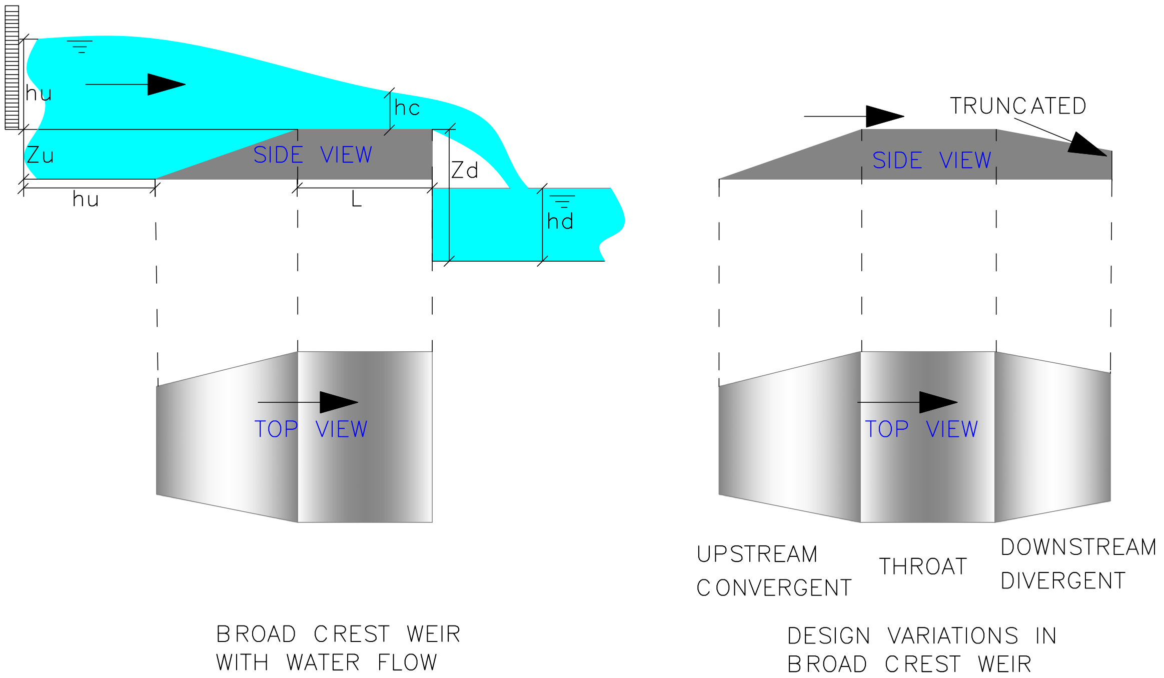


FIGURE III/3.5.0-1 Broad-crest weir. *Based on G.P. Markkley, Broad Crested Weirs, Lecture 9; Bie 5300/6300 Lectures. http://ocw.usu.edu/Biological_and_Irrigation_Engineering/Irrigation___Conveyance_Control_Systems/6300__L09_BroadCrestedWeirs.pdf.*

discharge coefficient and C_v is an approach velocity coefficient. The discharge coefficient C_d is a function of the upstream head over the sill h1, the sill length L in the flow direction, the crest width b, and the roughness of the flow surface. Bos proposed empirically the formula for C_d with the help of surface roughness (for a well-finished surface it would be around 0.003−0.005). The approach velocity coefficient C_v has been established in terms of length L and width b.

3.5.3 DESIGN BASIS FOR BROAD-CRESTED WEIRS

The following are a few points that need to be considered for designing and placement of measurements to obtain precise measurements.

1. **Sill requirements:** The following important points should be taken into consideration.
   - *Sill height:* Sill height should be above the upstream bed to provide flow for the entire range of operation, but should not be so high as to unnecessarily raise the upstream height. Therefore, optimum height selection is extremely important.
   - F_r^2 should be <0.2 in the upstream channel.
2. **Upstream/downstream:** The following are important issues:
   - The upstream converging slope H:V should lie between 3:1 to 2:1 to avoid hydraulic head loss and unnecessary turbulence.
   - Diverging downstream slope H:V should be between 4:1 to 6:1 truncated, as shown in Fig. III/3.5.0-1 (right-hand side figure), especially for 6:1 to avoid a long downstream. This is important as most of the loss takes place in the downstream.
   - The side slope of the throat section is normally the same as that of the upstream section, but in some cases, especially in earthen channels, there is a shorter throat width and zero side slopes like that shown in Fig. III/3.1.0-1I.
3. **Selection of site:** For precise measurement, proper selection of the site is important, so the following points should be taken into consideration.
   - Upstream of the broad crest should be fairly straight and of uniform cross-sectional channel.
   - Stilling chambers with measurement arrangement avoid fluctuations but are somewhat costly compared to an in situ gage [24].
   - Downstream obstructions such as gates should be avoided. Also it should not be located downstream of any gate/Tee.
   - Stable upstream is necessary to avoid recalibration and sediment collection.
4. **Other design considerations:** There are a few other design considerations as listed below:
   - Normal minimum and maximum limits of ratio of h/L are 0.075 and 0.75, respectively [24].
   - The lower limit has been put in place to take care of the reasonably smaller head loss to upstream head ratio.
   - The higher limit prevents nonhydrostatic pressure distribution.
5. **Bos proposition:** Bos (1976) considered broad-crested weirs similar to that shown in Fig. III/3.1.0-1I, i.e., without convergent and/or divergent sections. The front face of the weir at the top is not sharp but with a curved surface, as shown, with radius around $0.2H_1$. Some of his suggestions for practical use are as listed below.
   - Upstream head (h) ≥0.06 m or ≥0.05 L whichever is greater.
   - Sill nose radius r = 20% total head.
   - Broad crest width within the range of 2−20 total head (H_1).
   - Width greater than total head, or 0.3 m or L/5, whichever is higher.
   - To ensure modular flow total upstream and downstream heads should maintain specific ratio as given in Fig. III/3.5.0-2.

So far discussions have been limited to the nonlinear relationship of discharge with upstream head change. In the following section discussion will be on the proportional relationship of discharge with head.

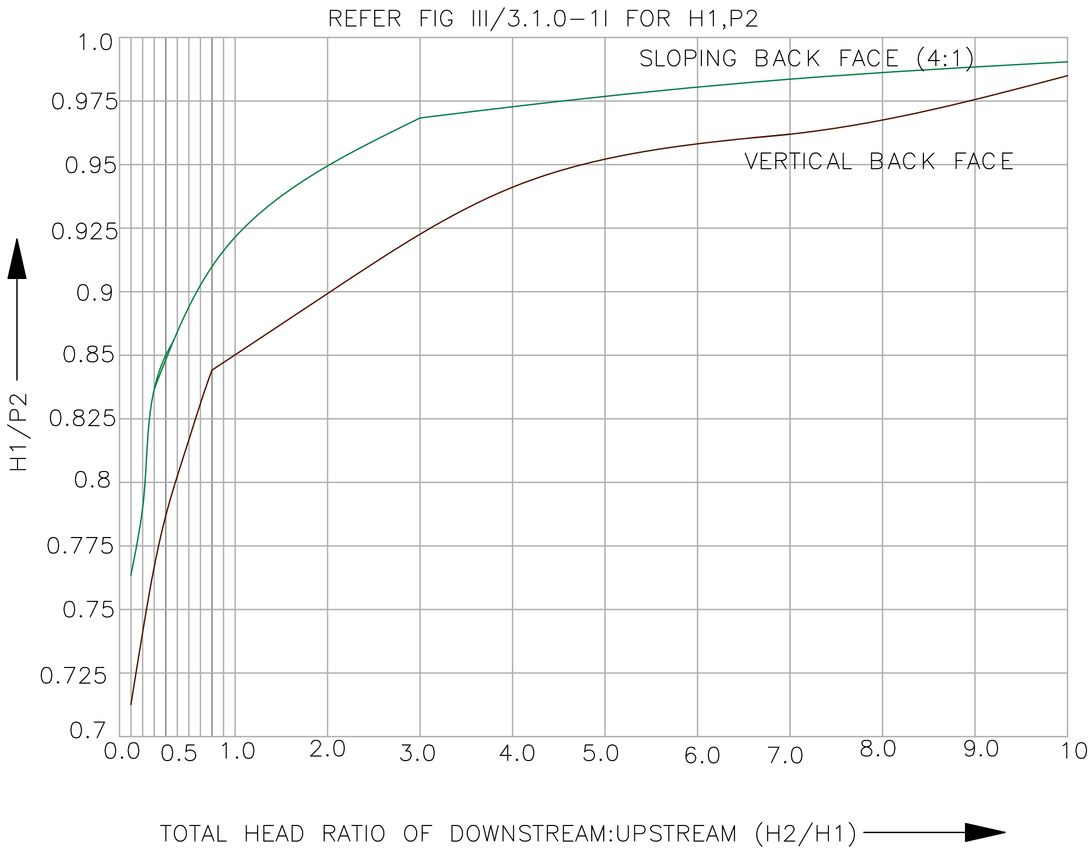


FIGURE III/3.5.0-2 Modular limit of broad-crested weir.

3.6.0 Sutro Weir

On account of their inherently weak structure and tendency to clog with debris, Sutro weirs are not used very often. When installed in a rectangular channel, the proportional-flow, Sutro weir regulates flow in such a manner that the discharge is linearly related to the upstream depth. This means that upstream velocity is constant. In view of this it is often used at an outlet control device in sewage treatment plants. The geometry of the weir is depicted in Fig. III/3.1.0-1G and the discharge equation is given in Eq. (III/3.1.1-9) in Table III/3.1.1-1 i.e., $q = C_d \cdot b \cdot \sqrt{ga}\left(h - \frac{a}{3}\right)$. Here, the discharge coefficient C_d is a function of a and b parameter of the geometrical figure. So, if one plots from the table of values for C_d in terms of a and b one would get a family of curves as shown in Fig. III/3.6.0-1.

Bos (1976) recommended a practical design with limits as follows:

$h \geq 2a$ or ≥ 0.03 m whichever is higher; $a \geq 0.005$ m and $b \geq 0.15$ m; $B/b > 3$; with the downstream water level at least 5 cm below crest water.

This concludes this brief discussion on weirs as well as primary devices and open-channel hydraulics and discussions will now center on sensors pertinent to open-channel flow measurement.

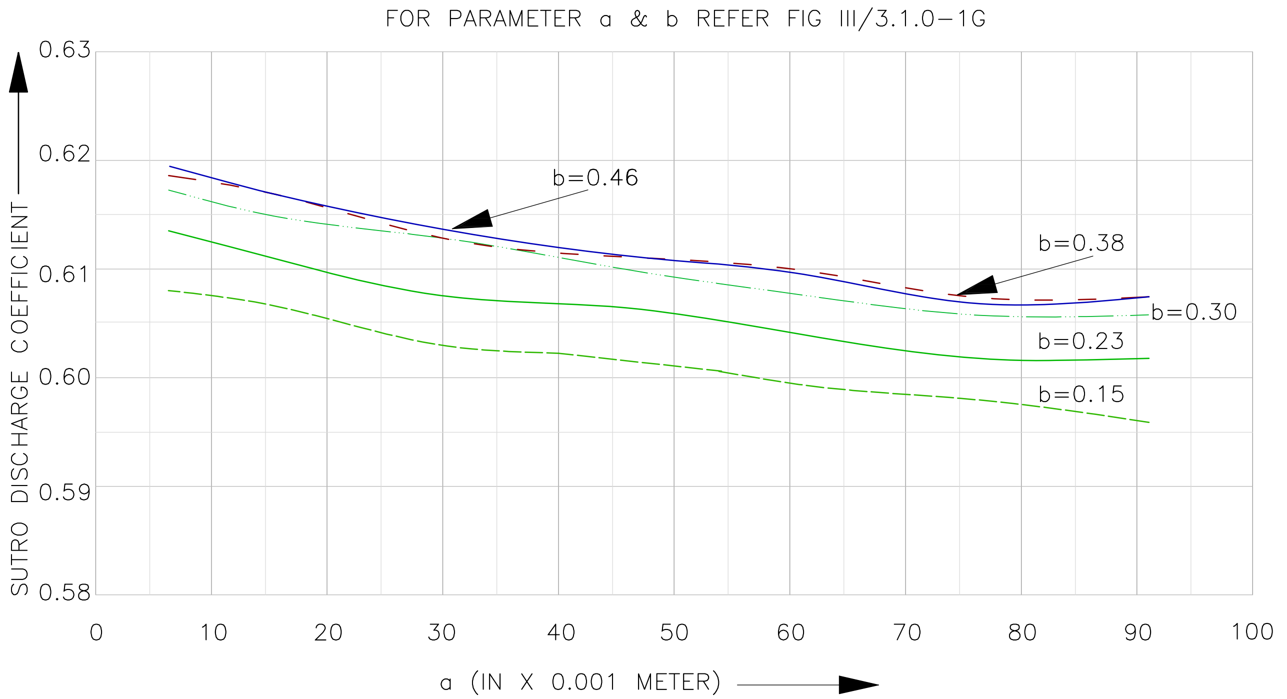


FIGURE III/3.6.0-1 Sutro weir discharge coefficient.

4.0.0 SECONDARY INSTRUMENTS FOR OPEN-CHANNEL FLOW MEASUREMENT

The discussion so far has been restricted to the principles of fluid mechanics/hydraulics, and primary devices for open-channel flow measurements. In order to complete flow measurements, a few secondary gages and/or instruments are essential. In this section discussions will be presented on these.

Open-channel flow measurements are basically an open system and not pressurized. In the course of the flow path, liquids are open to the atmosphere at some point. The liquid may be entirely open to the atmosphere, or may be contained within a closed pipe that is not full of liquid and only open to the atmosphere at the installation point of the flow meter itself [25]. Irrespective of the flow path, one thing is clear from the previous discussions for open-channel flow measurements, level, i.e., head measurement(s), must be deployed to compute flow with the help of discharge equations discussed in earlier sections of this chapter. In some cases velocity is also measured. In the case of free-flow a single head measurement will do while for submergence/submerged flow two head measurements would be necessary. Flumes and weirs are two primary devices normally used to measure open-channel flow. In these methods, primary devices are used along with a transducer and transmitter. The wetted primary devices are meant to restrict the liquid flow stream. Under liquid flowing conditions, this restriction would cause a rise in liquid level at a location either upstream or within the flow meter. Transducer(s) mounted on or near the primary device is required to sense the level. This signal from the transducer is processed in an electronic unit to measure and compute flow. Due to the limited application, demands for accuracy of measurement, there are not many types of devices and also construction materials are typically limited to those that target these applications. In the following subsection discussions shall be presented on different types of transducers and sensors.

4.1.0 Sensor Details

As already discussed in Section 2.1.7, there are a number of technologies which could be applied to measure the head at the upstream of the channel. Starting from the basic principles, all of these will be looked at. One of the major devices by which head is measured is a staff gage. In a staff gage the liquid level is directly read from the gage itself. So in this no transducer technology is involved, yet it is considered to be a reliable method of measurement. This is discussed at length in Section 4.1.2 of this chapter. However, prior to that, working principles of various transducers discussed in subsequent subsections are enumerated.

4.1.1 SENSOR PRINCIPLES

In this section working principles of different devices are discussed. There are two main basic principles of measurements. In this open system, the head or level is measured; one is direct level measurement and the other is indirect measurement of hydrostatic pressure to infer the level. In an open system hydrostatic pressure is measured by the hydrostatic head multiplied by density and acceleration due to gravity. So, $P = h \cdot \rho \cdot g$, where h is head/level of liquid, ρ is the density, and g is acceleration due to gravity at that place. Also level measurement by other means e.g. Ultrasonic/capacitance level measurement. These principles are discussed here.

1. **Mechanical level instrument:** In industrial applications, float and displacer type level indications have been quite common for a long time. The same principle is applied for monitoring levels in the upstream (and if necessary downstream) of an open channel to compute open-channel flow. In a float measuring system, Archimedes principle is used. The float on the liquid surface displaces a certain volume of liquid resulting in an apparent loss of weight due to the buoyancy force. In a float type instrument, a float moves up and down on account of changes in the level of liquid by the balancing action of the weight and thus follows the liquid level. The apparent weight of the float is balanced by the weight attached to the measuring wire through a pulley. This pulley is mechanically connected to a CAM or another set of pulleys, which is connected to an indicator or recorder to show and record the level in the stilling chamber. These are depicted in Fig. III/4.1.1-1A and Fig. III/4.1.3-1. The counterweight is also used to maintain the tension in the wire.

   A displacer type level sensor also Archimedes principle is utilized. The change in liquid level results in a change in the buoyancy force. The displacer level instrument detects these changes in the buoyancy force. As the liquid level increases there will be increased buoyant force and when the liquid level decreases the buoyant force decreases. The movement of the displacer is restricted by a spring. LVDT can be used to detect the rise and fall of the displacer and provide an output signal. Also, torque tubes can be used to detect the buoyancy force and provide an indication.

   Of these two methods the float type is more popular for open channel flow measurement.
2. **Ultrasonic instrument:** There are variations in measuring and computing open channels by ultrasonic instruments. In its simplest form, ultrasonic instruments are placed above the free water surface. The trans-receiver sends ultrasonic signals from the transmitter, which travels through the air to meet the open-channel water surface, in which the ultrasonic wave is reflected and travels to the receiver. The transit time is monitored and sent to the ultrasonic level/head instrument, which is one of the most common types of direct level measuring instrument deployed in open-channel flow measurement. There are two types of ultrasonic instruments deployed here. One is deployed to measure the level and the other is for determining the velocity. A typical ultrasonic instrument for level measurement is shown in Fig. III/4.1.1-1B. A US transreceiver is deployed to measure the

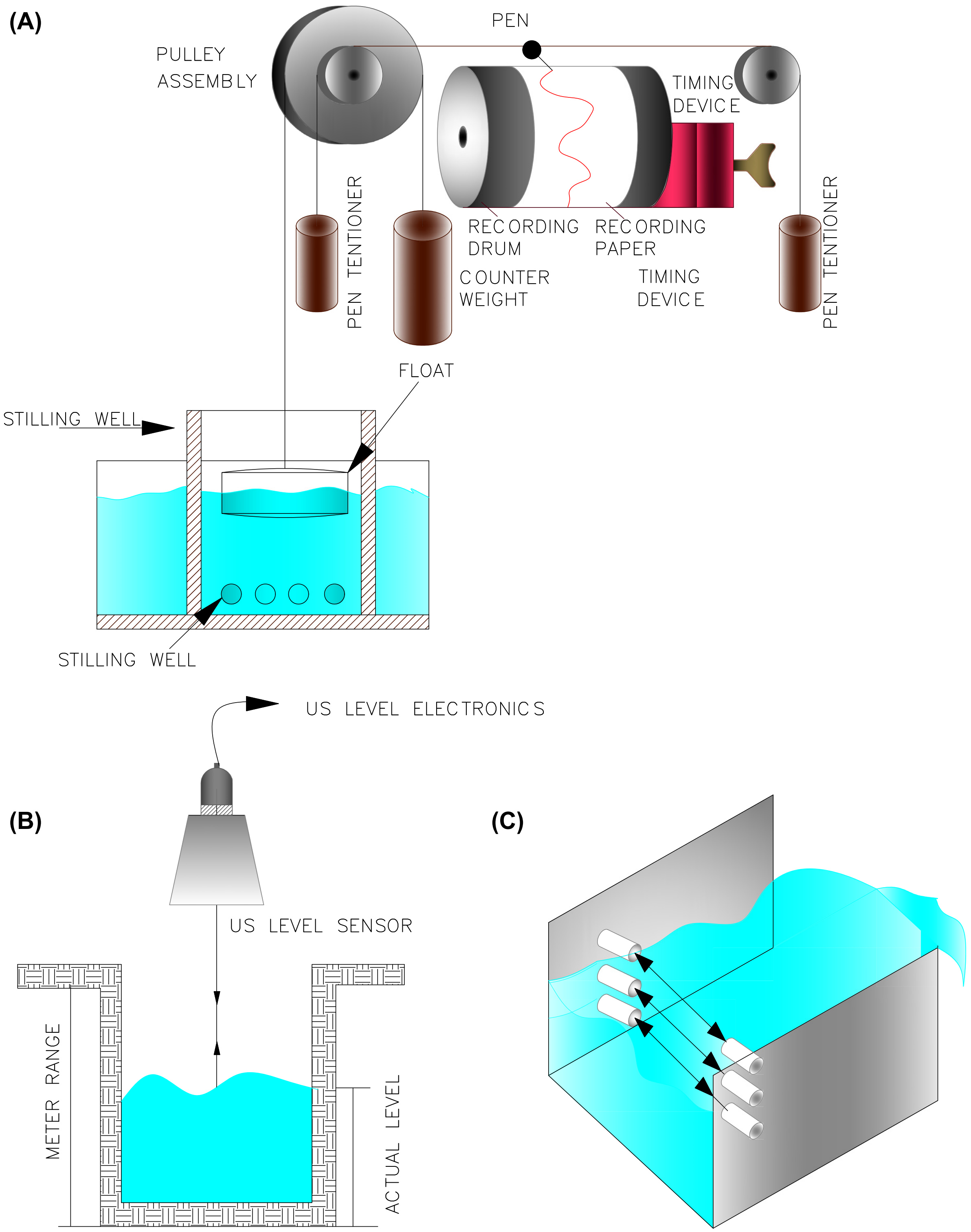


FIGURE III/4.1.1-1 Direct level instrument for open-channel flow measurement. (A) Float level instrument. (B) US for level. (C) US for velocity.

level or head for open-channel flow measurement. The sensor assembly is mounted at a specified place at a specified distance above the free water surface for level measurement. The sensor is connected to the remote electronics mounted in a safe place. This may be used only in upstream for free flow and for submerged flow two such sensors may be necessary to compute the flow.

Referring to Fig. III/4.1.1-1C one may note that here a separate sensor and detector sets are mounted on the wall of the open channel. Such transmitter receiver sets have been deployed to measure the velocity of liquids. As discussed in Subsection 3.1.3.4 in Chapter I, the differential travel time method, i.e., "time of flight," is utilized to compute the liquid velocity. The difference between the times of flight between the two transducers is directly proportional to the fluid velocity. Using the two transit times and the distance between the receiving and transmitting transducers L and the angle θ, velocity is given by Eq. (I/3.1.3-7). In such cases if a single transducer set is placed across the open channel then it can measure the velocity of liquid at a particular layer, not the average velocity; so, as shown in Fig. III/4.1.1-1C, a series of flow transducers are paired across the open channel and the combined velocities of the paired transducers are averaged to provide a true profile of the total flow path. The velocity signals are combined with level measurement for accurate measurement of flow in an open channel utilizing the Manning equation in a flow computer. If one now concentrates on a signal path between the paired transducers then it can be noted that the signal path can be reflected if there are a lot of particulates, bubbles, or debris in the flow stream. US Doppler effect is another means for flow measurement for open-channel flow. It also measures the instantaneous velocity components at a single point with relatively high frequency. Here flow measurement is also done by combining with level measurement as discussed above. Doppler techniques also measure the speed of particles coming towards the sensor. Particles in a stream move at different speeds and it is highly unlikely that it can measure all the particles in the stream, and hence does not represent the average flow in the stream, causing uncertainty in the overall open-channel flow measurement [25]. There are special Doppler effect US meters meant for open-channel flow measurements. Here a transducer is mounted on the floor of the channel and ultrasonic waves are beamed upstream against the flow. Like a normal Doppler effect meter the wave length of the reflected wave is compared to the emitted wave and the Doppler shift noted to translate into a velocity. There is an integrally mounted pressure transducer to continually monitor the depth of the channel. The cross-sectional area of the channel or flowing conduit is programmed into the electronics and from all this information an accurate flow measurement can be made [25]. It is worth noting that as transit time and Doppler US flow/velocity measuring instruments are discussed at length in Chapter V they are not discussed here, only principles and measurement issues are discussed here. For details on US flow meter for velocity measurements, discussions in chapter V may be referenced. In this chapter discussions are presented on US instruments for level measurement in Section 4.1.5.

3. **Capacitance/conductance level probe:** Capacitance/conductivity probes can also be used to measure the head/level in open-channel flow measurement. However, on account of some technical issues, they are not as popular as level measuring means.
   - *Capacitance probe:* Capacitance level instruments operate on the basic principle of the variation of a capacitor formed by the sensor, vessel wall (or another sensor), and dielectric material. If A is the plate area, d is the distance between the plates and the dielectric constant ε of the material between the plates. Then the capacitance, C, of the parallel plate capacitor is

$$C = \varepsilon A/d \qquad \text{(III/4.1.1-1)}$$

Bare probes can be used if liquid is nonconductive, otherwise the probe is coated in Teflon or another material. When the metal of the tank/channel can be utilized, a single probe can form the capacitance, otherwise two probes must be deployed. A capacitive probe is measured between the probes with the aid of a capacitance bridge which is excited by a high-frequency oscillator. In the portion out of the liquid, air serves as the dielectric, whereas in the immersed section, the dielectric is that of the liquid. When the liquid level changes there will be a large capacitive change. Therefore, the capacitance change is directly proportional to the level of liquid. The dielectric constant of the liquid should be known.

- The conductance method of liquid level measurement is based on the electrical conductance of the measured liquid which conducts a current with a low-voltage source (<24 V). Conductance is a relatively low-cost, simple method to detect and control the level. Normally a dual-tip probe is used to eliminate the use of a vessel/channel as a grounding medium.

4. **Pressure measurement:** As discussed earlier, hydrostatic pressure can be used to measure the level/head as long as density (ρ) and acceleration due to gravity (g) are constant. A pressure transducer is mounted in the bottom (slightly above the channel bottom-most part) in an open channel, or in a stilling chamber connected to an open channel. Since this is an open system (nonpressurized) pressure detected by the transducer is proportional to the level/head as long as ρ and g do not change. For pressure transmitter details, see Section 2.0.0 of Chapter XI. There are different technologies deployed for pressure monitoring/ differential pressure monitoring in pressure and differential pressure transmitters.

Differential pressure (DP) transmitters (DPTs) and pressure transmitters (PTs) are some of the most common and most useful pressure-measuring instruments in industrial applications. Almost all pressure transmitters are differential transmitters, with one port kept open to the atmosphere to measure and gage pressure. PTs/DPTs mainly operate on one of the following technologies:

- Force—balance principle;
- Strain gage;
- Differential capacitance;
- Change of reluctance;
- Piezo resistive;
- Resonant wire.

Previously, electronic transmitters based on force balance principles were in use, but now (except in pneumatic transmitters) the force—balance principle has become obsolete. However, the principle is described here. Pressure transmitters and differential pressure transmitters are discussed at length in this and other chapters. Short discussions on the operating principles of each of these technologies are presented: in this connection Fig. III/4.1.1-2 may be referenced.

- *Strain gage type:* As the name suggests in strain gage resistivity changes due to changes in pressure and hence strain. The sensors are normally connected to one Wheatstone bridge circuit as leg resistance. At zero pressure applied to the transmitter all the resistive legs of the bridge circuit are balanced, so when the circuit is energized, the voltages across specified output or test points are equal. When pressure is applied to the transmitter, the resistance of the strain gages changes and the bridge is unbalanced, creating a proportional differential voltage across the test points. The resistance of the strain gage element can be affected by temperature as well as applied stress, i.e., strain gage transducers are sensitive to temperature effects. Therefore, extreme care must be taken in the design of the primary element to minimize the ambient/process temperature effects. In modern transmitters a microprocessor in the primary element keeps the signature of

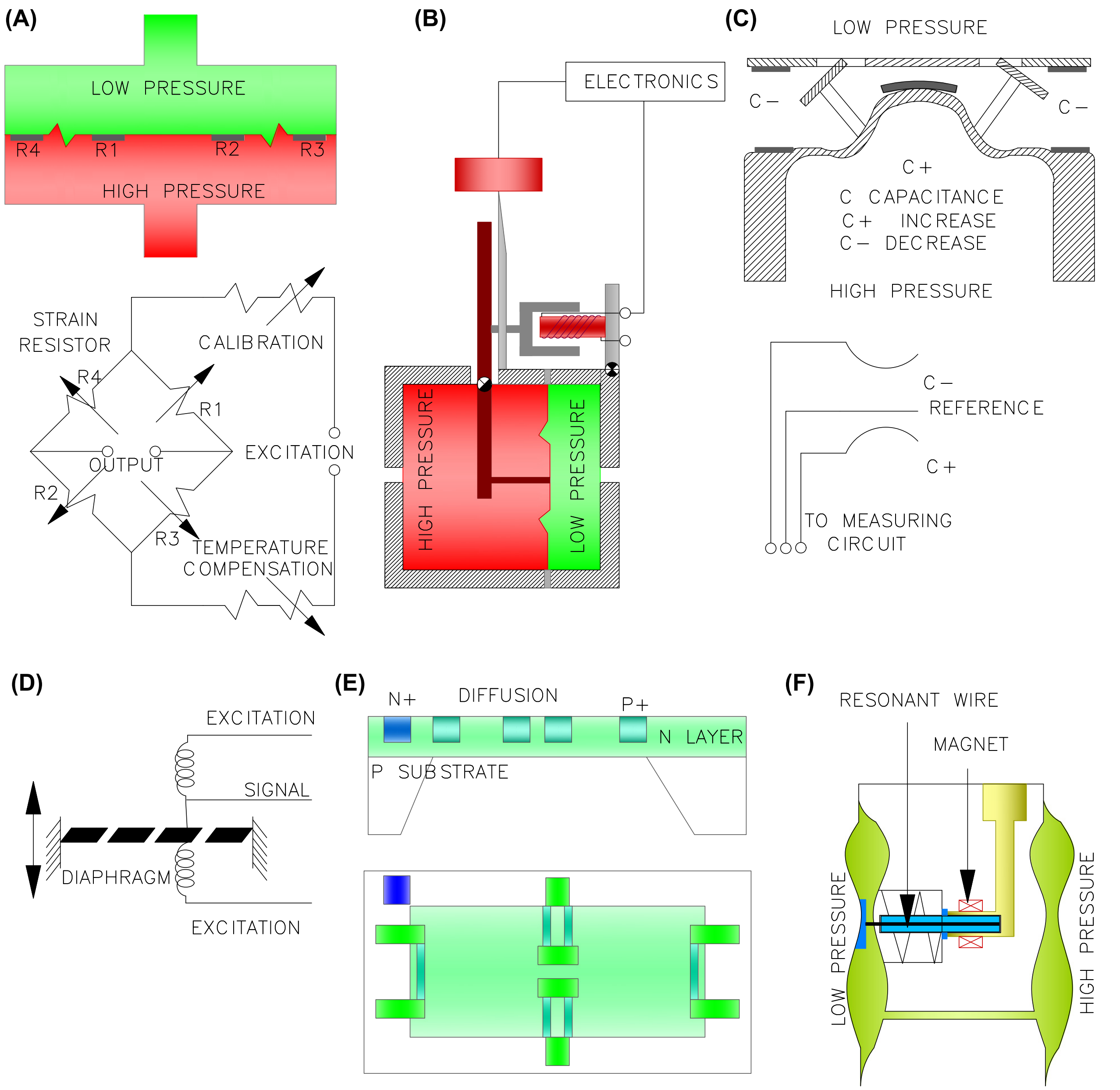


FIGURE III/4.1.1-2 Transducer principles. (A) Strain gage. (B) Force balance. (C) Capacitance. (D) Reluctance change. (E) Piezoresistive. (F) Resonant wire. *Based on an ABB document. Courtesy: ABB.*

variations or strain gage resistance with temperature and provides necessary compensation to the sensor for the same. The secondary electronics of the transmitter measures the unbalanced differential voltage across the test points to produce standard signal output. (Refer to Fig. III/4.1.1-2A.)

- *Force balance type:* As the name signifies, here the applied force due to differential pressure is duly balanced. The system consists of a diaphragm connected to the high and low pressure of the process externally, and internally it is connected to a force bar. There is a range bar which is pivoted and driven by a force coil to counteract the motion of the force bar. The pressure differential between the high- and low-pressure sides of the diaphragm generates a force which is applied to the

connected lower end of the force bar causing it to be displaced. As the force bar moves out of position, due to this applied force, a highly sensitive electromagnetic sensor detects it and causes an electronic circuit to send a different amount of electric current to a force coil. The force coil presses against the range bar which pivots to counteract the initial motion of the force bar. On account of this interaction force, the bar is returned to its original position (slightly less). Thus the force coil is in a new position due to the differential current in the coil. When the system returns to equilibrium, the milliampere current through the force coil will be a direct, linear representation of the process fluid differential pressure applied to the diaphragm. In the case of gage pressure, the low-pressure end of the diaphragm is open to the atmosphere to measure the gage pressure. On the other hand, for DPT two ends of the diaphragm are connected to the low and high pressure of the process. (Refer to Fig. III/4.1.1-2B.)

- *Capacitance type:* A capacitance type transmitter functions as a change in capacitance ratio in a differential capacitance arrangement. The process diaphragm is connected to the ceramic diaphragm of the differential capacitance arrangement, through the fill fluid in the capacitance sensor. This ceramic diaphragm is common to two capacitors (of differential capacitor arrangement) formed by two plates on either side of the diaphragm. Pressure or DP between the two ports causes displacement of the ceramic diaphragm. This change in distance is very small but causes the change in the ratio of the two capacitances (in differential capacitor arrangement) to feed the logic circuit of the transmitter. In the secondary electronics section processes this change in signal produces the standard signal output. (Refer to Fig. III/4.1.1-2C.)
- *Reluctance type:* Similar to the capacitance type, here also the process diaphragm, which is magnetically coupled to a pair of inductances, causes the change in magnetic coupling (hence an inductive value of two inductances) of the paired inductance system. A magnetically coupled process diaphragm is mounted between the two coils. On account of pressure or DP between the two ports of DPT, the sensing diaphragm will deflect toward one coil and away from the other. So, due to the change in the position of the process diaphragm, the magnetic flux density of the closest coil will be enhanced. At the same time, the magnetic flux density of the furthest coil will be decreased. Therefore, due to the increase in the magnetic flux density of a coil, there will be an enhancement of the induction and impedance of that coil. Meanwhile the induction and impedance of the other coil will decrease. These changes in inductance values of the two coils will be processed at secondary electronics to produce a standard signal. (Refer to Fig. III/4.1.1-2D.)
- *Piezoresistive type:* The piezoresistive sensor functions similar to that in the strain gage discussed earlier. This is the electronic version of a strain gage which offers much more sensitivity, being nearly 100 times more sensitive than a metallic strain gage. This is a semiconductor element whose conductivity is influenced by extremely small mechanical deformations due to force/pressure. A semiconductor element in a wafer format is used as the sensor and shows very high sensitivity. Like in a gage the strain sensitivity in semiconductors is temperature-dependent. Therefore, temperature compensation as discussed in a strain gage must be deployed. Piezoresistive sensors offer advantages such as high sensitivity, good linearity at constant temperature, and track pressure changes without hysteresis. However, these have certain limitations also, such as higher initial offset, nonlinear dependence on temperature, and drift with temperature. (Refer to Fig. III/4.1.1-2E.)
- *Resonant wire:* In a resonant-wire pressure transducer a wire is fixed by a static member at one end, and by the sensing diaphragm at

the other. An oscillator circuit is used to cause the wire to oscillate at its resonant frequency. When pressure or DP between two ports is applied, the tension of the resonant wire also changes. This change in wire tensions changes the resonant frequency of the wire. A digital counter circuit detects the shift. This change in frequency can be detected quite precisely, so, this type of transmitter is suitable for a wide range of applications. The most significant advantage of the resonant wire pressure transducer is that it generates an inherently digital signal, and therefore can be sent directly to intelligent control systems. (Refer to Fig. III/4.1.1-2F.)

The working principles of pressure and differential pressure transmitters are the same, therefore these descriptions are applicable for differential transmitters as well as multivariable transmitters discussed in Section 2.1.0 of Chapter XI. The reader is advised to refer to the said section to get a comprehensive idea of process transmitters.

The secondary electronics of the transmitter (especially for intelligent transmitters) shall include but is not limited to the following:

- Filtration, amplification, signal compensation, linearization, and conditioning;
- Convert signal and generate standard 4–20 mA DC output;
- Support local display of different forms;
- Develop digital signals for standard protocol, e.g., HART/fieldbus systems (e.g., Profibus, Foundation fieldbus);
- Communication with a universal handheld configurator.

4.1.2 STAFF GAGE

Normally, all open-channel flow-monitoring points are provided with one staff gage for a quick indication of the level at that point.

1. **Description:** Like a measuring tape, a staff gage is also a measuring tool. For a quick and easy visual indication of the water level and flow all level-monitoring stations are required to have a staff gage from which the water level can be easily read to compare with any other data obtained. For the following reasons, porcelain enameled gages are preferred to other types of printed gages:
   - Resistance to rust, discoloration corrosion, and marine growth;
   - Longer life;
   - Quick washability for algae, marine growth, etc.

   Normally these are permanent gages with black bars on a white background. These static gages do not require power, however, they should be properly illuminated so that can be seen during dark periods and at night. Enameled gages are mounted on a board made of wood (redwood, cedar) or a synthetic board with the help of a suitable hole and grommet of suitable material. A typical staff gage is depicted in Fig. III/4.1.2-1. As seen in this figure, normally staff gages are available in a

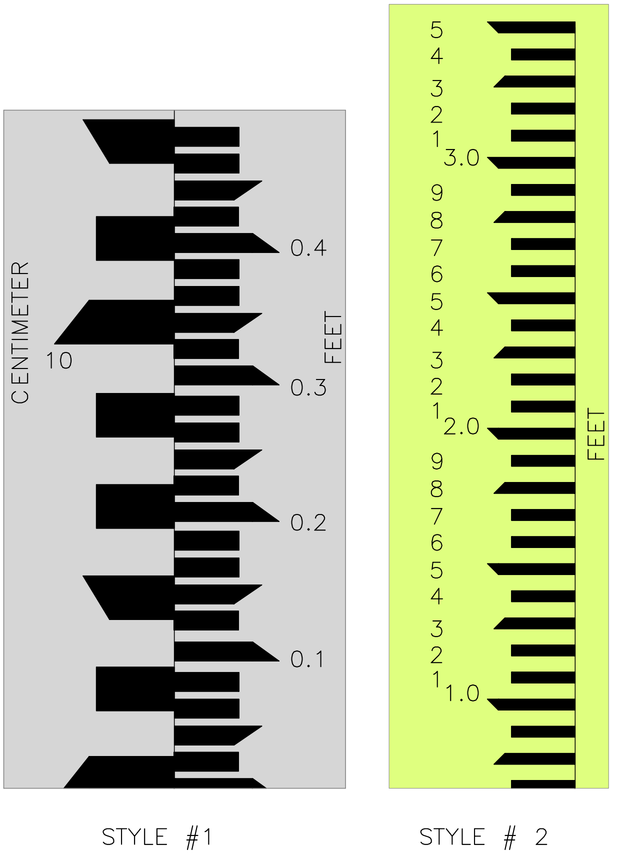


FIGURE III/4.1.2-1 Staff gage.

combination of feet and centimeter units. In the gage there are three types of bars. Depending on the various styles some are meant to indicate:

- The longest bar down-turned point: 1/10th feet;
- Mid-length bar up-turned point: 1/20th feet;
- Shortest bar and white space: 1/100th of feet.

Indicated below is a typical style shown on the left-hand side of Fig. III/4.1.2-1.

One can choose the style and unit best suited for the application from a wide variety of staff gage styles offered by the manufacturer. Nonvertical style is also available. Unless calibrated, nonvertical installation requires equal spacing of graduations.

2. **Specification:** Brief specifications of a staff gage are presented in Table III/4.1.2-1.
3. **Mounting and installation:** The staff gage is fixed at a suitable place so that it is clearly visible from a long distance. The mountings are normally vertical, Other inclined types are also possible. Necessary precautions should be taken while tightening the screw to fix the scale on the board so that the porcelain enamel does not crack.

Another on-site level-measuring instrument is the mechanical float type instrument discussed in the following section.

4.1.3 MECHANICAL LEVEL INSTRUMENT(S)

In this subsection discussions shall be put forward on the float type mechanical level indicator and recorder. Prior to starting these discussions the reader is referred to Fig. III/4.1.3-1 which depicts the basic arrangement of a mechanical level instrument. For mechanical recording, Fig. III/4.1.1-1A may be referenced. The discussion begins with a description of the system.

1. **Description:** In an open channel it is always better to measure the level in the stilling well if possible. Direct level measurement of open channels is not uncommon. This author has experienced both types, i.e., Parshall flume level measurement in a stilling chamber at

TABLE III/4.1.2-1 Staff Gage Specification

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Technology	Visual indication scale	Local visual	
2	Purpose	Site water level		
3	Mounting	Vertical/inclined		
4	Board	Scale on board material: wooden, synthetic Scale fixed with board by suitable grommet		
5	Material	Sheet steel 2 mm/1.9 metal core with baked on porcelain enamel finish/cast aluminum 5 mm thick		
6	Scale length	Customer choice	To specify	
7	Scale style	To specify		Special feature
8	Scale type	Feet/cm/combination		
9	Scale	White finish with black markings		To specify for other color
10	Accuracy	~2 cm		

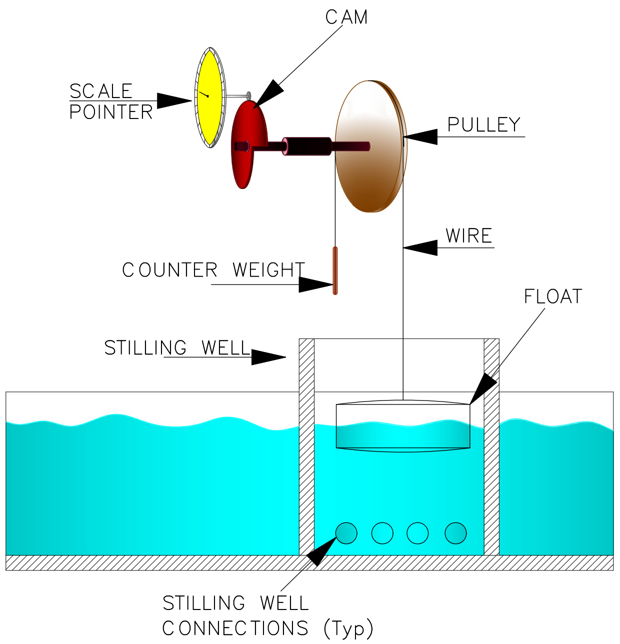


FIGURE III/4.1.3-1 Mechanical float-operated meter.

NALCO Angul (Mechanical sensing) and also one on the channel itself at ITC Tribeni West Bengal (US Sensor). These references are given here because stilling wells actually serve as mechanical filters to dampen energetic waves. This is especially important for mechanical type sensing. The stilling well, usually set in the bank of the channel and connected to it by one or more intakes (sometimes directly in the stream), accommodates and protects the float. It is meant to eliminate (or reduce) the effect of surface waves and short period surging in the channel. For the principles of operation for a mechanical float type, Subsection 4.1.1.1 may be referenced. A complete measuring system consists of one graduated scale with a pointer, pulley assembly, connected tape/wire, guide wire, one float, and a counterweight. In the case of a recording system there will be another set of a pulley assembly, recording drum, mechanical clock as a timing device, recording chart, etc. The float pulley is mounted on a support and accommodates the tape in the circumferential groove. The tape is fastened to the upper side of the float and runs slip-free over the pulley. It is kept tight by a counterweight. In the figure a circular scale pointer (dial) type indicator has been shown but it could equally be a vertical scale with a pointer also. Normally floats are provided with stainless steel guide wire (not shown). A short description of the various components is given below. The details given are based on standard IS 9116:2002.

- *Float:* Cylindrical leak-proof highly stable floats are used. The size of float depends on the application and accuracy required. Reasonably large floats are recommended to reduce the ratio of inertia and frictional resistance in the gage height element, and for better representation of buoyancy force. As per IS 9116:2002 floats may vary from 125 to 300 mm in diameter (further details are available in Annex B of the standard).
- *Float line counterweight:* A float line attached to a float is also connected to a counterweight to maintain proper tension. The float pulley is turned during changes in water levels. This motion is imparted to the stylus (or drum or encoder) or to the indicator pointer. The float line is graduated and its extension due to the weight of the float and counterweight is insignificant.
- *Recording and timing device:* The level can be recorded in a chart and put on a recording drum as shown in Fig. III/4.1.1-1A. This recording may be analog type (a graphical representation of level changes with time) or it could be digital type with coded parameter values. The timing for the recording system is normally a simple clock mechanism and it drives the recording drum. A stylus is connected to the main pulley through a gear/pulley system. The clock mechanism can be driven by a spring or weight. Alternatively, it can be electrically operated either from the mains or a battery.

2. **Specification:** A brief specification of a mechanical level-measuring system is enumerated in Table III/4.1.3-1.
3. **Installation issues:** The well should be vertical with sufficient height and depth so that free movement of the float is ensured. The top of the well should be much higher than the maximum flood level. The well and all construction joints of the well and intake pipes should be watertight so that water can enter or leave only by the intake itself. From IS 9116:2002 it can be seen that the float gage installation should permit measurement of the stage to be made at all levels from below the minimum range to above the maximum range anticipated. Installation should be such that accuracy is not worse than ±10 mm or 1% of range.

4.1.4 ONLINE PRESSURE SENSOR/TRANSDUCER

On account of their compact size, lower overall cost, and easier installation, online pressure transducers may be used in place of normal

TABLE III/4.1.3-1 Specification for Mechanical Float Type Instrument

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Measuring range	As per application <30 m		
2	Working pressure	Atmospheric		
3	Working temperature	(–) 20 to 100°C		
4	Process temperature	Up to 200°C		
5	Least count	<2 mm		
6	Indication type	Dial/vertical scale pointer		
7	Mechanical counter	optional		
8	Scale	Cast aluminum scale		
9	Graduations	Inches/feet or cm/meter		
10	Recording type	Analog/digital		As applicable
11	Timing device	Clock		
12	Clock	Spring/weight/electric		
13	Clock accuracy	<±30 s/day		
14	Guide wire	304/316 SS 3 mm		
15	Float size	As per relevant standard		(<400 mm)
16	Bottom anchor	Steel (mild steel)		
17	MOC* float	Stainless steel SS316/304		*MOC: Material of construction
18	MOC* counterweight	Rust-proof noncorrodible		
19	MOC* measuring rope	SS316		
20	Sheave elbow roller	Cast aluminum		
21	Pulley	Glass-filled nylon		
22	Protection class	IP55 or better		

pressure transmitters to measure the hydrostatic pressure to compute upstream/downstream level/head in open-channel flow measurement.

1. **Description:** These online electronic pressure transducers convert an applied pressure into a standard 4–20 mA DC signal for secondary usage such as intelligent controls, recorders indicators, etc. Silicon semiconductor strain gage/piezoresistive sensors (see Subsection 4.1.1.4 of chapter III) are commonly used for this type of transmitter. State-of-the-art surface mount technology with silica gel protection in the electronic circuitry is now commonly used. The compact, rugged design makes these instruments suitable for various applications, including liquid level measurement at the site directly mounted at the bottom of the channel/stilling well. These should be vibration/shock- and moisture-proof. As shown in Fig. III/4.1.4-1, a wide range of electrical connections and process connections are available to cater for the various site requirements. The majority of these transmitters are all-welded stainless steel (SS) measuring cells, with a compact case to make the transmitter more robust. The compact case is also made of stainless steel and is available with environmental protection. A flush diaphragm process connection is suitable for liquid with dirt or for corrosive applications.
2. **Specification:** Table III/4.1.4-1 lists the specifications for an online pressure transducer.
3. **Mounting and installation:** The mounting of an online pressure sensor is shown in Fig. III/4.1.4-1 and is a very easy fit type as per the process connection chosen.

Another common way to measure and level the head in an open-channel flow measurement is by using ultrasonic technology. Since flow or velocity measurement utilizing ultrasonic technology has been discussed at length in Chapter V, here ultrasonic level monitoring is mainly discussed.

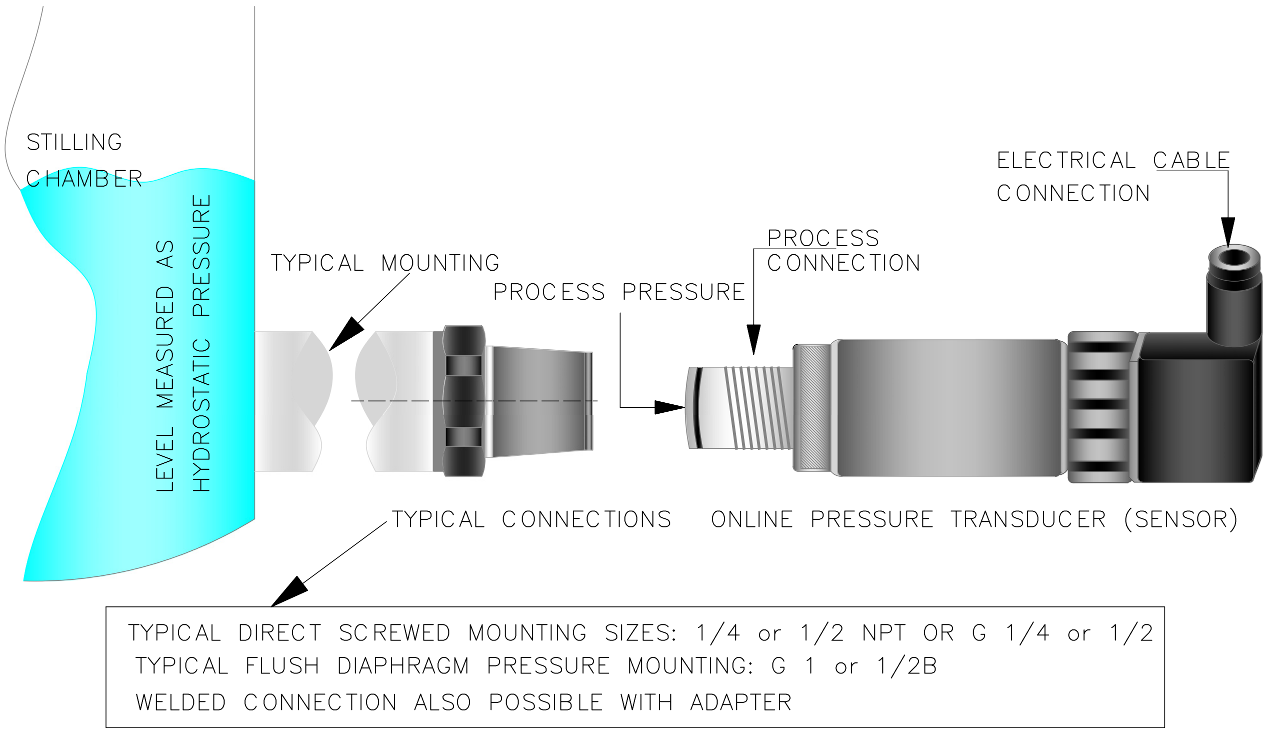


FIGURE III/4.1.4-1 Online pressure sensor (transducer).

TABLE III/4.1.4-1 Specifications for an Online Pressure Transducer

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Pressure range	Application dependent		
2	Burst pressure	>6 times pressure range		
3	MOC wetted parts	SS 316 (-17-4 PH)		MOC—materials of construction
4	MOC casing			
5	MOC flush diaphragm			
6	Internal fluid	Silicone oil		
7	Power supply	24 VDC (10–30 VDC)		
8	Output	4–20 m ADC		
9	Zero/span	Adjustable over the range		
10	Response time (90%)	<10 ms		
11	Accuracy	<0.2% AR		
12	Repeatability	<0.1%		
13	Stability	<0.2% for 12 months		
14	Ambient temperature	(–)20 to 80°C		
15	Shock/Vibration (g)	IEC 60068-2-27/6		
16	Process connections	As per Fig. III/4.1.4-1		
17	Electrical connection	4-pin connector ISO4400/DIN 43650 L connector DIN 175301/1/2 in NPT-m		Data from standard manufacturer
18	Enclosure class	IP 65 min		
19	Hazardous application	Yes		Manufacturer standard

4.1.5 ULTRASONIC LEVEL SENSING SYSTEM

In this section short ultrasonic level sensing systems deployed for open-channel flow measurement are discussed. While going through the chapter it has been noted that it is possible to use a level meter to measure the flow through this channel by measuring the level and using the established relationship. This conversion is performed in the remote electronics of an ultrasonic sensing system.

1. **Description:** An ultrasonic sensing system is a noncontact level-sensing system. The measured value is converted into a rate of flow in the flume and weir. Since the flow equations are different for different types of flumes and weirs, the conversion and linearization curves and algorithms will be different. Level-sensing systems need to have different algorithms. Therefore, special US sensing systems may be required. The majority of US sensing systems available are preprogrammed,

such as the linearization program for different types of flumes and weirs. An ultrasonic sensing system consists of sensor and remote electronics.

- *Sensor:* Sensors have a different range of measurements and different beam angles. Usually sensors have a built-in temperature compensation system. As sensors handle sonic waves they should have a suitable acoustic window material. Depending on the energy level, sensors have different measuring ranges and beam angle and attenuation levels. Eco-frequency varies with sensors but normally these are within a short band or range. Sensors should be designed for outdoor applications with a wide operating (ambient) temperature. Sensors have standard process connections but, as shown in Fig. III/4.1.5-1B, for open-channel measurement sensors can be easily mounted

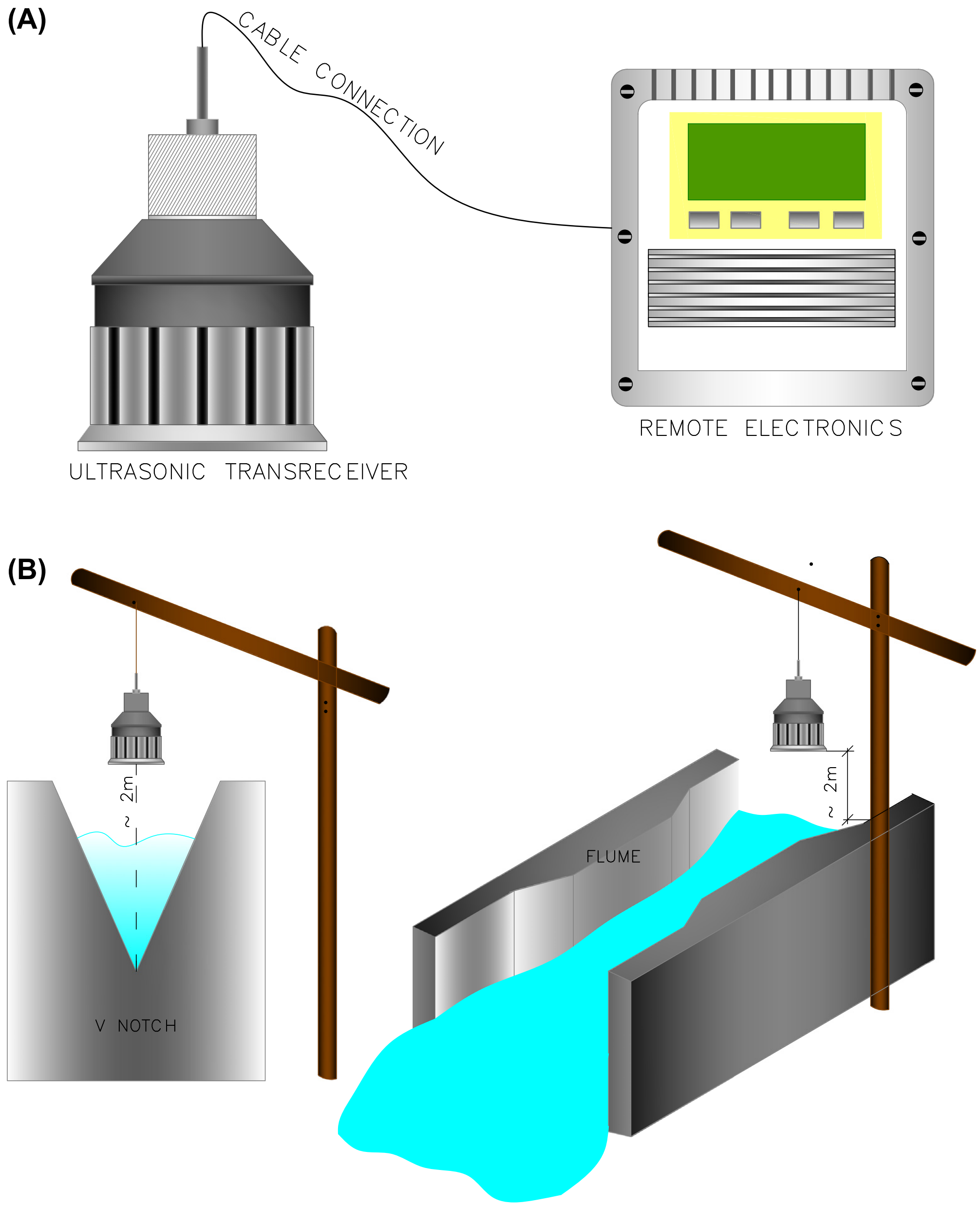


FIGURE III/4.1.5-1 Ultrasonic level measurement. (A) Ultrasonic sensing system. (B) Ultrasonic sensor mounting.

on the top of a channel and/or stilling well with the help of vertical and horizontal poles as shown. However, they should be mounted at a specified distance above the water surface so that the instrument system can function properly.

- *Remote electronics:* Remote electronics are normally wall-mounted or panel-mounted. This remote electronics unit is not only a signal processing unit, it also provides the operator interface unit. Basically this is a controller which, based on selection, provides standard output for the selected flume/weir. The remote electronic unit has suitable display as local indication. Normally these electronic units are provided with the necessary communication means to communicate with intelligent control systems. RS 232/485 and mod bus are standard means to establish communication. Since these are means for an operator interface they have user-friendly menus and provisions for updating the system. Most of these modern units are IT-compatible. A typical connection of remote electronics with a sensor along with sensor mounting has been depicted in Fig. III/4.1.5-1. The figure also shows the display and operator interface in front of the remote electronics.

2. **Specification:** A short specification of a US level-sensing system is given in Table III/4.1.5-1.

TABLE III/4.1.5-1 Specification of Ultrasonic Level Instrument

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Measuring range (flow)	>0−25 × 10^6 m^3/h		
2	Measuring distance	0.5−15 m		
3	Damping rate	−0.1 to 50 m/min		
4	Window material	Glass reinforced epoxy		
5	Housing	Polyester/PVDF/ETFE		
6	Operating frequency	40−50 KHz.		
7	Beam angle	7−10 degrees		
8	Process temperature	(−)20 to 100°C		
9	Temperature sensor	Integral sensor and built-in compensation		
10	Process connection	1″−2″ NPT/G or ANSI flange		
11	IP rating	IP68		
12	Extension cable	Normally provided		
13	Remote electronics	Panel/wall mounting		
14	Output	HART/4−20 mA DC fieldbus		
15	Relay output	Normally relay outs are available* with contact rating 3 A @30 VAC or 0.5 A@ 24 VDC or better		*for interlock/ alarm
16	Power supply	24 VDC		

Continued

TABLE III/4.1.5-1 Specification of Ultrasonic Level Instrument—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
17	Accuracy	0.15% range		
18	Repeatability	<0.1% range		
19	Communication	RS 232/485 with MODBUS		
20	Cable connection	½″ NPT, M20 × 1.5		
21	Certification	Hazardous condition		
22	Display	120 × 64 dot graphic LCD display		
23	Operator interface	Dedicated membrane keys		

It is worth noting that the data given are from standard manufacturers and actual data may differ from these data

4.1.6 BUBBLER TYPE LEVEL MEASUREMENT

Bubbler level measurement systems have been briefly discussed in Subsection 2.1.7.5 above. Bubbler level measurement systems are recommended for measuring levels of water with large quantities of suspended solids or sewage, such as drainage water. They are also used in applications where there is corrosive liquid, foam, solid debris, sewage sludge, or turbulence and ultrasonic, float, or displacer type systems are ineffective. Bubbler tubes provide a simple and inexpensive but moderately accurate level-measurement system.

1. **Principle of operation of Bubbler level instrument:** As shown in Fig. III/4.1.6-1, a bubbler tube is immersed to the bottom of the vessel (stilling well) in which the liquid level is to be measured. A gas, referred to as purge gas (normally compressed air—instrument quality or an inert gas—usually nitrogen) is passed through the bubbler tube. If the vessel (in our case the stilling well) is empty, the gas/air will escape freely at the tube end, creating pressure inside the bubbler tube (the same as atmospheric pressure). When the liquid level in the stilling well increases, the liquid will create pressure at the base and side walls of the tank. Therefore, it will also create pressure at the opening of the bubbler tube which will increase with an increase in the liquid level. This means that the hydrostatic pressure of the liquid will try to restrict the escape of purge gas from the bubbler tube. Therefore, in order to maintain the same flow of purge gas through the bubbler tube, its pressure has to be increased to overcome the liquid pressure. In other words, there has to be constant DP to keep parity with the level change. As shown in Fig. III/4.1.6-1, there is a DP regulator in the arrangement. The DP regulator is used to maintain a pressure which just overcomes the hydrostatic pressure with a few bubbles. This bubble flow of purge gas is set and indicated by the associated purge rotameter (see Section 9.1.0, Chapter II, Fig. II/9.1.4-1B) shown in the figure. Thus, at the top of the bubbler tube the pressure can be sensed and this is almost the same and proportional to the liquid level in the vessel, or stilling well in our case. Therefore, a pressure sensor (transmitter) detects

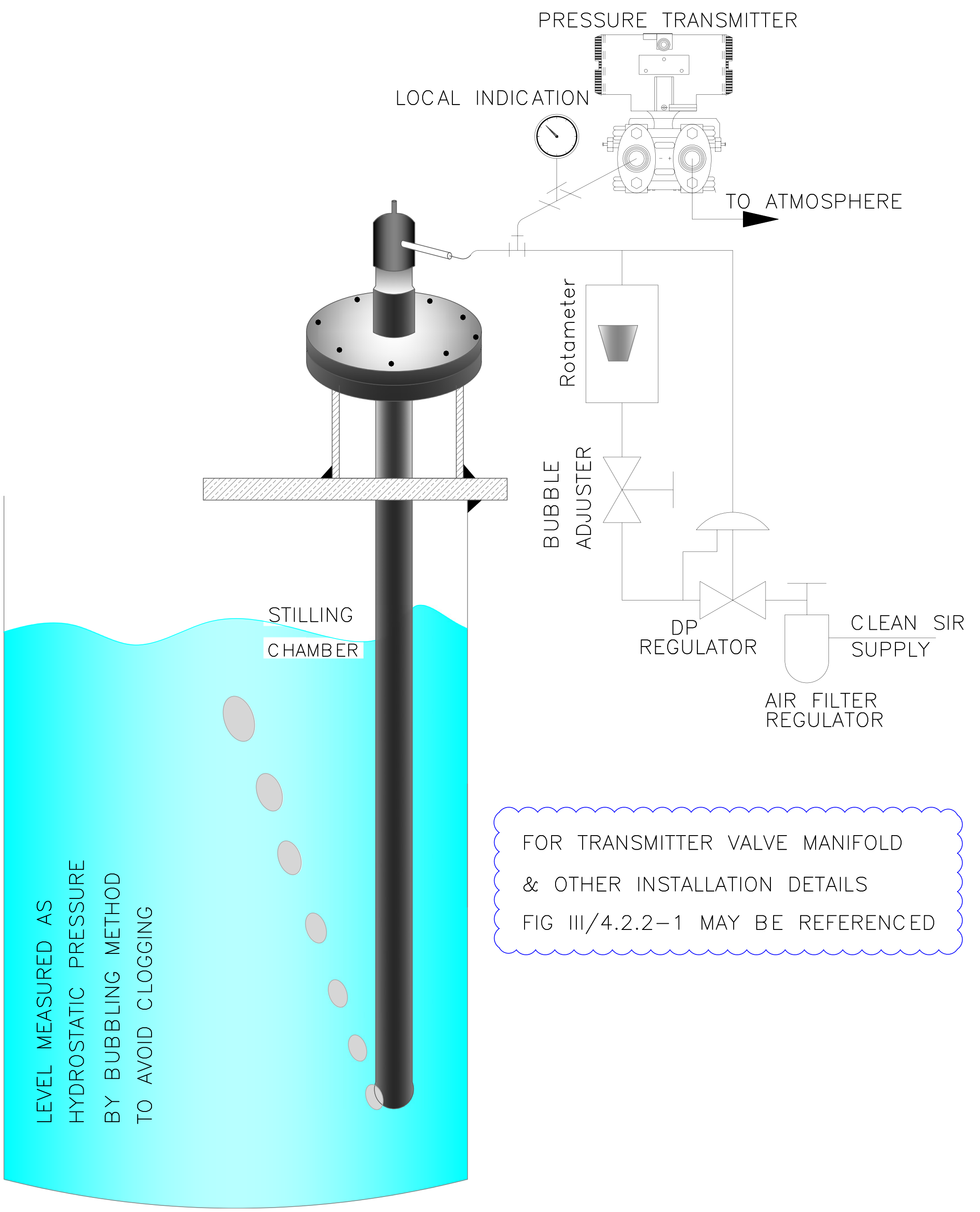


FIGURE III/4.1.6-1 Bubbler level instrument.

changes in pressure as the level changes. In Fig. III/4.1.6-1 one pressure transmitter (section 4.2.0 of this chapter) and one pressure gage are shown. While the former can be used as a device for remote transmission and the second gives local indications (this can be achieved by local indicator of pressure transmitter also, without gage also). Although reasonably accurate level measurement can be obtained without liquid entering the bubbler tube, bubble tube blockages still occur.

2. **Features of a bubbler level instrument:** Listed below are a few merits and limitations of this instrument.
   - *Advantages:* The advantages include:
     - Bubbler level instrumentation set up is simple;
     - It is an inexpensive solution to level/pressure measurement for use with corrosive fluids, liquids with suspended solids/dusts—to eliminate the chances of line clogging;
     - It is intrinsically safe;
     - It can be used for high-temperature applications.
   - *Disadvantages:* The following are a few disadvantages of the instrument:
     - Requirement for purge gas supply and associated piping at the place of installation;
     - Build-up of material on the bubbler tube cannot be eliminated totally;
     - Maintenance-prone;
     - Measurement is susceptible to being affected by density variations, freezing, and plugging.
3. **Components of a bubbler level instrument system:** As can be seen in Fig. III/4.1.6-1, there are a number of components in the measurement system. These are:
   - Bubbler tube;
   - Purge gas/instrument air as required;
   - Pressure transmitter;
   - Pressure gage;
   - Purge rotameter;
   - DP regulator.

   Out of these bubbler tubes is a simple 6 (sometimes 12) mm diameter dip tube made of SS or copper tubing. To keep the pressure drop low in the tube, the bubble flow rate is maintained (generally not exceeding 1.0 SCFH). A pressure gage is not required for pressure transmitters with local indications. For the rotameter and purge rotameter, Section 9.1.0 of Chapter II and Fig. II/9.1.4-1B may be referenced. A pressure transmitter has been elaborated on in Section 4.2.0 of this chapter. The DP regulator is discussed in the following subsection.
4. **DP regulator:** The basic purpose of a DP regulator is to maintain a constant DP across the purge rotameter so that there is constant flow across it. The regulator allows constant flow to be maintained in a system in which the inlet and mainly the outlet are subject to pressure fluctuation (especially when the level changes). As shown in Fig. II/9.1.4-1B, the DP regulator consists of an inlet and an outlet separated by a diaphragm. At the inlet side, compressed air (purge gas) enters through a restrictor (referred to as a regulator) pressed against a spring. In the output side there is one spring and outlet port. When there is no level, compressed air from the air filter regulator enters the DP regulator and escapes through the bubbler tube. At this point the DP regulator is in a balanced condition by the outlet spring force with inlet supply pressure. When the level increases gas flow is disturbed, i.e., air flow is restricted, causing an increase in back pressure. As a result of increased back pressure the diaphragm is pressed downward against the spring (tension). With spring tension, the diaphragm is pushed, causing displacement of the regulator from the inlet port and forcing more gas to gush in to balance the additional hydrostatic pressure (due to the level increase) and restoring the spring position and gas flow set at the rotameter. Therefore, the new air pressure at the outlet corresponds to the new level (hydrostatic pressure). The pressure in the outlet line is sensed by the pressure gage and pressure transmitter. The pressure/level transmitter measures the pressure required to force air through the tube and generates the standard output signal, which is proportional to the depth of the liquid.

   With this discussion on various level-sensing systems concluding, we now look into the details of pressure transmitters, which play an important role in level measurement.

4.2.0 Pressure Transmitter

In open-channel flow measurement the level/head is measured to compute the flow following with an associated flow equation for each type of flume/weir. In this connection Section 2.0.0 of Chapter XI may also be referenced. Also, in Subsection 2.1.7.3 the relationship between hydrostatic pressures and the level/head has been established. Therefore, the role of the pressure transmitter in open-channel flow measurement cannot be overestimated. There are various technologies and principles used in measuring pressure in a pressure transmitter. These principles are discussed in Subsection 4.1.1.4 in this chapter. Therefore, further elaboration of pressure transmitter operation is unnecessary. In this section a short description and specification of transmitters is given.

4.2.1 TRANSMITTER DESCRIPTION

Transmitters can be divided into three major sections. These are: the middle section (transducer body and primary [pri.] electronics), top section (secondary [Sec.] electronics and adjustment part), and lower section (process parts and sensing capsule). The various components of each part are described in Table III/4.2.1-1. The information listed below is from different reputed manufacturers, so there may be variations in specific transmitter types. Also, these are only guidelines, for further details the manufacturer should be consulted.

A typical transmitter is shown in the leftmost part of Fig. III/4.2.1-1. In this figure the transmitter is shown with both high and low process ports intentionally to indicate that all pressure transmitters are basically DPTs with one port

TABLE III/4.2.1-1 Major Components of DPT/PT

SL	Transmitter Section	Transmitter Components
1	Top section: sec. electronics	Housing
2	Top section: sec. electronics	Front cover (window cover)
3	Top section: sec. electronics	Rear cover
4	Top section: sec. electronics	Display unit (LED/LCD with keys)
5	Top section: sec. electronics	Terminal block
6	Top section: sec. electronics	Push button unit
7	Top section: sec. electronics	Communication board (behind display)
8	Middle section: TB[a] and pri. electronics	Transmitter body
9	Middle section: TB[a] and pri. electronics	Sensor unit
10	Middle section: TB[a] and pri. electronics	Transducer unit with diaphragm
11	Middle section: TB[a] and pri. electronics	Primary electronics
12	Middle section: TB[a] and pri. electronics	Transducer gasket
13	Lower section: process parts and SC[b]	Gasket
14	Lower section: process parts and SC[b]	Isolating diaphragm
15	Lower section: process parts and SC[b]	Process flange
16	Lower section: process parts and SC[b]	Flange adapter
17	Lower section: process parts and SC[b]	Drain vent valve

The U bolt, mounting bracket, etc. are also part of transmitters for mounting of the transmitter.
[a]TB, *trans body.*
[b]*Sensing capsule.*

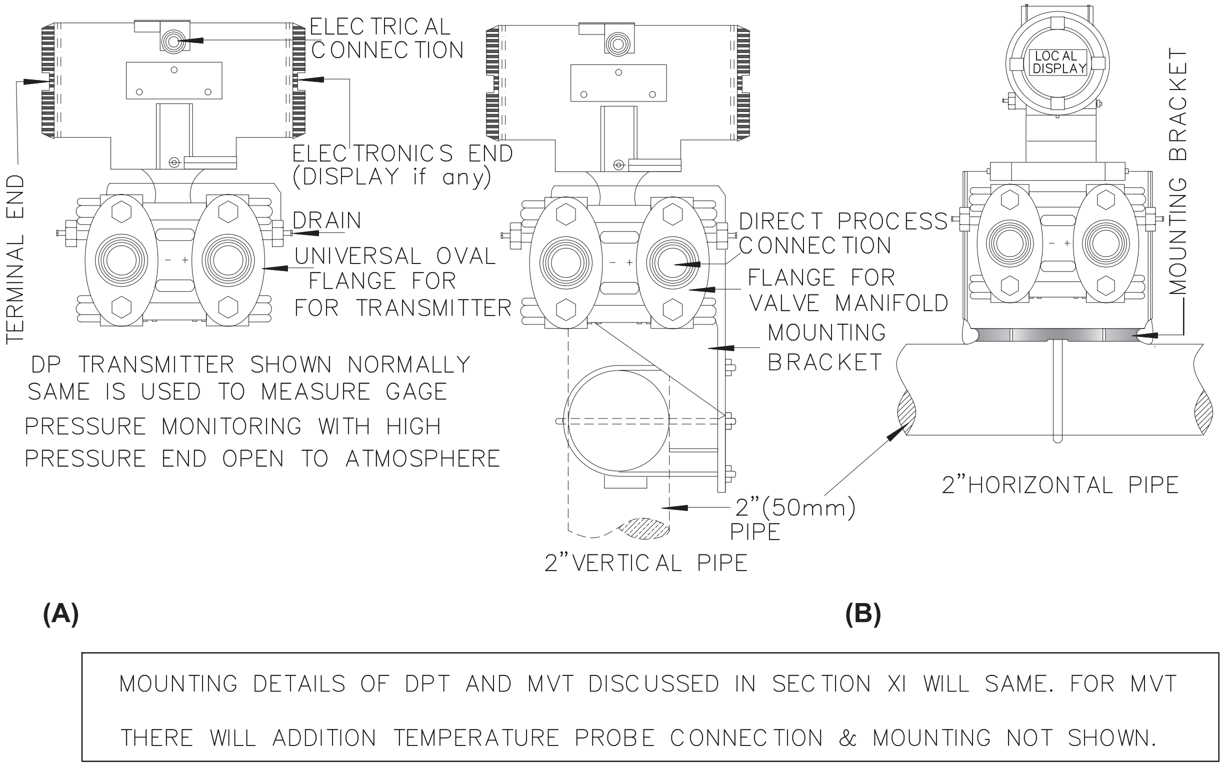


FIGURE III/4.2.1-1 Pressure transmitter with mounting. (A) Pressure transmitter (PT). PT mounting in 2″ pipe. *Taken from S. Basu, A.K. Debnath, Power Plant Instrumentation and Control Handbook, Elsevier, November 2014. http://store.elsevier.com/Power-Plant-Instrumentation-and-Control-Handbook/Swapan-Basu/isbn-9780128011737/, Courtesy: Elsevier.*

open to the atmosphere. Often pressure transmitters are provided with a blind flange in the port open to the atmosphere.

Transmitters now offer a number of facilities to process control engineers. Modern transmitters offer:

1. Very high performance;
2. IEC61508 certified safety integrity level (SIL)
3. Powerful diagnostics;
4. Local operator interface;
5. Communication in HART Protocol and fieldbus system.

4.2.2 SPECIFICATION

Table III/4.2.2-1 gives a short specification for a pressure transmitter.

TABLE III/4.2.2-1 Pressure Transmitter Specification

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Sensor technology	Manufacturer standard		Subsection 4.1.1.4
	Material specification			
2	Isolating diaphragm	SS 316, Alloy 276, Monel, etc.		
3	Sensor & wetted parts	SS 316, Alloy 276, Monel, etc.		
4	Housing	Cast aluminum		

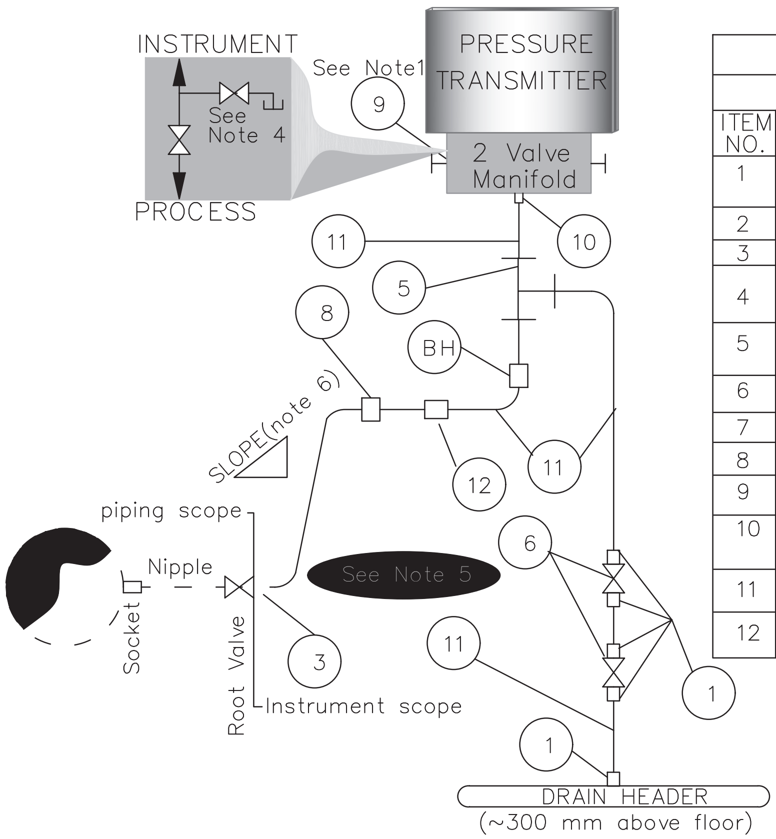
Continued

TABLE III/4.2.2-1 Pressure Transmitter Specification—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
5	Cover/flange/process connector	ASTM CF- 8M		
6	Filling fluid	Silicone oil		
7	Min/max span and range	Application-dependent* Span ratio at specified accuracy may be lower		*60:1 is common
8	Zero/span adjustment	0%–100% min		
9	Process connection	¼″ or ½″ NPT or G ½		
10	Electrical connection	¼″ or ½″ NPT or G ½ M20×1		
11	Output	4–20 mA HART protocol		
12	Fieldbus	Profibus/foundation		Common
	Performance specification			
13	Accuracy	0.055% FSD min		
14	Repeatability	0.052% FSD		
15	Stability	0.005%/(>) 5 years		
16	Power supply effect	0.005%/V		
17	Response time*	90 ms (dead time ~40 ms)		Dead time included
18	Ambient temperature	(–)20 to 70°C		
19	Power supply (load*)	24 VDC (10.5–40 VDC)		*Load varies with supply
20	SIL certification	IEC61508: SIL-2/3		
21	Self-diagnostic	CPU/Hw failure		Hw: Hardwire
22	Certification	Hazardous services		
23	Display &OP interface	LCD display intelligent		OP: Operator
24	Operator interface			
25	Mounting	2″ horizontal/vertical pipe		
26	Accessories	Valve manifold, mounting Bracket, bolts etc.		

4.2.3 MOUNTING AND INSTALLATION

A 2″ pipe mounting as shown in Fig. III/4.2.1-1 (middle and right-hand side figures) is common with pressure transmitters and DP transmitters. If applicable when the transmitters are mounted in local enclosure, same mounting style also holds good. A typical pressure transmitter installation has been shown in Fig. III/4.2.3-1. Here the transmitter is shown above the source point. This is common for open-channel applications.



DRAWING IS NOT TO SCALE

ITEM NO.	BILL OF MATERIALS ITEM DESCRIPTION
1	SOCKET WELD TUBE CONNECTOR TO MATCH TUBE SIZES.
2	SUITABLE ADAPTER
3	3/4" / 1 X 1/2" SW REDUCER
4	1/2 / 3/4 " IMPULSE PIPE SCHEDULE & MATERIALS: See Note5
5	1/2 / 3/4 " EQUAL TEE FITTING (for tube connection)
6	1/2" / 3/4" Socket Weld GLOBE VALVE
7	NOT USED
8	1/2" / 3/4" PIPE UNION
9	2 VALVE MANIFOLD (FORGED)
10	VALVE MANIFOLD ADAPTER (Say Male Connector)
11	1/2" / 3/4" SS TUBE
12	1/2" / 3/4" PIPE X TUBE UNION

NOTE

1) INTEGRAL VALVE MANIFOLD (VM) IS PREFERRED & SHOWN, OTHERWISE EXTRA TUBES AND FITTINGS WILL BE REQUIRED

2) BULK HEAD(BH) IS THE INTERFACE BETWEEN FIELD & ENCLOSURE (IF APPLICABLE), AFTER BH, TOWARDS Tx IS. INSIDE ENCLOSURE (IF APPLICABLE) WHERE IMPULSE LINE IS SS TUBE. IN CASE ENCLOSURE NOT APPLICABLE THEN BH IS NOT REQUIRED

3) IMPULSE PIPE AT SOURCE TERMINAL POINT i.e. AT ROOT VALVE/ REDUCING INSERT, SOCKET WELD CONNECTION IS PREFERRED TO AVOID CONNECTION MISMATCH.

4) THIS VALVE COULD BE USED AS, DRAIN, TEST AND LINE FILLING UP PURPOSE ALSO.

5) VALVE, FITTINGS MATERIALS & RATING: AS PER APLLICATION

6) SLOPE GENERALLY 80mm per 1000mm

FIGURE III/4.2.3-1 Pressure transmitter installation. *Adapted from S. Basu, A.K. Debnath, Power Plant Instrumentation and Control Handbook, Elsevier, November 2014; http://store.elsevier.com/Power-Plant-Instrumentation-and-Control-Handbook/Swapan-Basu/isbn-9780128011737/. Courtesy: Elsevier.*

In the installation diagram, which is self-explanatory, impulse tubes are shown along with a bulk head (BH) intentionally to show that the impulse line could be an impulse tube or pipe. It is also shown to indicate the field and enclosure interface, if applicable. If there is no enclosure the BH and impulse tube may be avoided, i.e., the impulse pipe can be used. Integral valve manifolds, especially for DPTs, are always preferred. A two-valve manifold has been shown separately.

This concludes the discussions on secondary instruments, as well as open-channel flow measurement. Discussions will be reverted back to closed pipe flow to focus on positive displacement flow meters.

LIST OF ABBREVIATIONS

ABS Absolute
AR Actual reading (in connection with accuracy)
CHU Constant head unit
DP Differential pressure
DPT Differential pressure transmitter/transducer
EGL Energy grade line
ETFE Ethylene tetrafluoroethylene (type of plastic)
FSD Full scale division (in connection with accuracy)
HGL Hydraulic grade line
ID Internal diameter
LHS Left-hand side
LIE Local instrument enclosure
LVDT Linear variable differential transformer
NB Nominal bore
OD Outer diameter
PVDF Polyvinylidene fluoride − plastic type
RF Raised face or radio frequency
RHS Right hand side
RTD Resistance temperature detector
RTJ Ring tongue joint
SIL Safety integrity level
SS Stainless steel
US Ultrasonic/United States
USRB United States Bureau of Reclamation
VM Valve manifold
WRT With respect to

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CHAPTER IV

POSITIVE DISPLACEMENT (PD) TYPE FLOW METERING

Chapter Outline

1.0.0 POSITIVE DISPLACEMENT METERS: GENERAL DISCUSSIONS

Positive displacement (PD) meters are more popular for liquid flow applications, but are also used in gas applications. This is because they are more suitable for higher-viscosity applications. By the late 1930s PD meters had been in use for custody transfer applications. Although positive displacement metering technology is an old application it still enjoys about 8%−9% of the total major flow meter market (Fig. I/5.0.0-1). Positive displacement flow metering technology is the only flow metering technology which gives

Plant Flow Measurement and Control Handbook. https://doi.org/10.1016/B978-0-12-812437-6.00004-4

the volume flow directly, without the need for any flow computations. Therefore, it is easier to register the total volume mechanically. All positive displacement meters are named after the mechanical device inside their respective chamber. However, because of the principles of measurements there is a rotating component in all positive displacement meters, hence maintenance issues in the case of positive displacement meters should not be underestimated.

1.1.0 PD Meter Working Principles

As stated earlier, positive displacement metering technology gives direct measurement of volume flow. A measured quantity of fluid volume fills a bucket and within a fixed time lapse, the same fluid is discharged into the downstream system in a periodic manner at a specified time. By measuring the number of buckets filled and discharging into the downstream in a set time one can compute the volume flow to the downstream. Positive displacement flow meters execute exactly this same function. Positive displacement flow meters entrap a fluid in a fixed/measured volume of container and discharge the same into the downstream, repeatedly, in a periodic manner. The number of times that the container is filled and emptied gives an indication of fluid flow through the flow meter. Many positive displacement flow meter geometries are available [1]. Therefore, positive displacement meters measure volumes of fluid per unit time or flow by counting repeatedly the filling and discharging of known fixed/measured volumes. A typical positive displacement flow meter comprises a chamber to obstruct the flow. Inside the chamber, there will be a rotating/reciprocating mechanical unit with a number of fixed/measured containers to create fixed/measured volume discrete parcels from the passing fluid. The rotating parts form moving seals between each other and/or with the flow chamber body. These seals need to be tight enough to prevent any leakage of fluid. These seals also help in entrapping the fluid in the fixed container associated with the rotating/reciprocating mechanical unit, so that fluid cannot pass through the meter without being measured. In some positive displacement flow meter designs, bearings are used to support the rotating parts [1]. Therefore, by counting the number of discrete parcels discharged, the volume of the fluid flow through the chamber can be obtained. The greater the fluid flow, the more will be the number of discrete parcels discharged through the meter body. The counting of passing discrete parcels of the rotating/reciprocating mechanical device can be sensed mechanically (for example, by a gear system) and/or electronically by a suitable detector. PD flow meters are precision instruments whose internal moving components are mass-balanced yet remain hydraulically imbalanced [2]. Therefore, the meter can measure very low quantities of fluid without the need for external power, since the energy needed for the meter is drawn from the flowing fluid. Mainly clean viscous fluids are measured by positive displacement flow meter. They can offer accuracy up to 0.1% full-scale division (FSD). Also, from the measurement principles, it is clear that positive displacement flow meters can also be used in the measurement of intermittent flow.

1.2.0 Positive Displacement Meter Description

There are several types of different positive displacement flow meters, so a general description of positive displacement flow meters is not possible. However, a few common parts are observed in each type of positive displacement flow meter and these are discussed here.

1. **Housing:** The housing is the pressure vessel in the belly of which there are measurement elements. Measurement elements vary with the type of PD meter. Obviously, there is one inlet port and one outlet port. Through the inlet port the fluid is channeled into the measurement element. Similarly, through the outlet port, after measurement, the fluid is channeled out from the measuring element. The pressure rating for the housing varies based on the system pressure, temperature, as well as the

metallurgy of the housing. When there is a separate external housing (and the measuring element is different), it is known as double-casing construction. In double-casing PD meters, there is an outer casing with a measuring casing fixed inside. The advantages offered by double-casing meters include:

- The measuring chamber walls only sense the delta pressure across the meter inlet and outlet, which allows for thinner chamber walls with less distortion.
- System piping/pressure stresses are absorbed by the external case and the measuring chamber does not experience the pressure effect.

In single-case PD meters the housing serves as both the pressure vessel and measuring element, i.e., a single-case meter has the housing and the measuring chamber walls as one integral unit.

2. **Measurement chamber:** The measuring chamber (element) is designed as per the principles for PD meters. The packed or known quantity of fluid volume is separated and the same flows through the measuring chamber. Each measurement chamber has its own unique characteristics, including accuracy, friction loss, pressure drop, debris tolerance, driving torque, and size/weight [3].
3. **Double-casing design:** In double-casing design there is an external casing to the measuring chamber to eliminate the pressure differential of the measuring element. Some of these meters are double-casing designs, so that the measuring element can be easily removed for hydro-testing and line flushing on start-up or for servicing [4].
4. **Mechanical registration:** Almost all PD meters have a mechanical register to account for volumetric measurement, from the PD meter output, i.e., to count the number of times the container is filled and emptied. The specific gear ratio calculates the known volume measurement into a unit of measurement. There is a calibration-adjusting mechanism for fine adjustments to volumetric flow.
5. **Pulse transmitter:** In order to transmit the signal to remote places pulse transmitters are normally deployed. Many instruments also provide analog electronic and/or HART or Fieldbus transmission facilities. Pulse transmitters are quite common in PD meters, and are designed to provide an accurate pulse output signal for remote signaling. Mechanical rotation of the flow meter is converted in the pulse transmitter to the ratio of electronic pulses per volume.
6. **Electronic flow totalizing:** An electronic flow totalizer/computer receives the pulse output of the PD meter, and provides one resettable and totalizer display. These are often also used for control in cases of batch processing. These are discussed at length in Chapter XI.

1.3.0 Advantages and Limitations of PD Meters

Positive displacement flow metering technology is quite old and has been used for different applications over time. In fact, it is preferred for custody transfer metering in oil and petroleum applications. These flow metering systems have a few advantages and disadvantages, which are now discussed.

1.3.1 ADVANTAGES OF PD METERS

Listed here are the major advantages of positive displacement meters:

1. Positive displacement flow meters can be used for both liquid and gas applications.
2. Relatively high accuracy ($\pm 0.1\%$) is possible in positive displacement flow meters. Compared to orifice plates, positive displacement flow meters offer better accuracy at lower flow.
3. Positive displacement meters have a high turndown ratio, especially for highly viscous fluid, e.g., 100:1 turndown ratio for water can give 3000:1 for very high viscous fluid (e.g., 200 cSt). It is possible to measure very low flow at a normal pressure drop.

4. Positive displacement meters can be used for highly viscous and corrosive fluids. Positive displacement meters are often preferred for measurement of hydraulic fluids.
5. There is no requirement for any straight run pipe for installation of positive displacement meters.
6. When properly maintained, they can give longer service life.
7. An accurate positive displacement flow meter has minimum leakage across the seal, and so is better for highly viscous fluids.
8. In gas applications it shows high accuracy over a wide range of applications.
9. Positive displacement flow meters can directly register cumulative flow (mechanical flow integration).
10. Positive displacement meters have low operating cost.
11. High pressure, up to 100 bar, is possible in positive displacement meters. Positive displacement flow meters find their applications in fluid temperatures up to ~200°C.
12. For custody transfer applications, especially in oil and liquid applications, PD meters are used extensively.

1.3.2 LIMITATIONS OF PD METERS

Listed below are the major limitations of positive displacement meters:

1. Positive displacement flow meters are suitable for clean fluids with a maximum filtration level of 100 μm, otherwise there are possibilities of it becoming blocked if large particles are trapped in the wrong place, such as the rotors being exposed to fluid.
2. One of the biggest disadvantages is that the meter size increases following the square law, so if there is an increase in the flow rate then the meter size is increased significantly i.e. in square of increase in meter size. For normal flow measurement 50 NB (nominal bore) is a common size. For custody transfer larger sizes are used.
3. PD meters usually have high permanent pressure loss.
4. In PD meters (e.g., oval gear meters) there are moving parts that work together to move material through them. The moving parts and bearings are prone to wear and tear. Any wear and tear could result in changes to the clearance dimensions causing errors. These meters are therefore maintenance-prone and often require part replacements.
5. In gas applications a major disadvantage is the maintenance cost.
6. This is a comparatively older technology, and there are a number of modern flow measurement technologies.

1.4.0 Factors Influencing PD Meter Performance

From the basics of PD meters it can be seen that in PD meters a discrete segment of flow is displaced and delivered to the outlet port of the meter. However, such displacements are influenced by a number of factors. Also, the performance of the meter is highly dependent on slippage through the meter. The greater the slippage, the greater the error in reading, and hence the poorer the accuracy. In this subsection short discussions have been put forward to address these issues to properly understand meter functioning.

1.4.1 FACTORS INFLUENCING VOLUME DISPLACEMENT IN PD METERS

There are basically four factors which are responsible for influencing volume displacement in PD meters, care must therefore be taken during the design and selection of PD meters.

1. **Temperature:** Whenever there is a change in temperature there will be a volume change (depending on the temperature increase/decrease there will be expansion/contraction) of the material forming the segments. This will cause changes in the displacement of the

meter, which are related to the volume expansion coefficient of the material forming the segments. If the moving parts are made up of some material (e.g., aluminum), and the static part is made up of another material then there will be more changes in displacement. Therefore, careful consideration should be taken to avoiding such an occurrence. Another limitation of meter operation may come from the temperature, which could also affect the viscosity.

2. **Viscosity:** If one recalls the discussions on viscosity in Chapter I it could be argued that on account of viscosity a liquid's film can cling to the surfaces of the measuring element. With an increase in the thickness of such a film, the displacement will be reduced up to a point when the film can get no thicker because of the wiping action of the parts. Further increases in viscosity have no effect on the displacement, and so during this period, a change in medium viscosity displacement will be effected. Changes in temperature can also cause changes to viscosity. Hence temperature and viscosity points discussed are also related.
3. **Coating:** Like the viscosity effect of liquid, any deposit can cause a reduction of the displacement of the meter. Such deposits may come from the process medium. In such cases suspended solids should be avoided by using a suitable filter. As long as the deposit thickness is constant it will have less of an adverse effect, the problem arises whenever there are changes in the deposit thickness. In the case of crude oil and paraffin wax the problem is very much more serious as paraffin wax has a melting point near the operating temperature [4] in many cases.
4. **Wear:** It is needless to say that an increase in the wear of the material forming the segment will increase the displacement. However, wear is a slow process and is somewhat predictable. With use of suitable materials and operating conditions, wear can be reduced to a great extent.

1.4.2 SLIPPAGE IN PD METERS

Slippage in PD meters is an important issue. For PD meter operation it is necessary that there be volume segments created by the moving measuring element parts and a static measuring chamber casing. In fact, there are capillary seals between these moving and static parts. Differential pressure across these parts causes a very small flow, which is never accounted for in the displacement. Such unaccounted-for flow is referred to as *slippage*. This slippage is affected by differential pressure, i.e., by flow rate and mechanical resistance offered from internal friction and dragging force and external accessories. As a result of these, slippage will vary, and hence error varies. Therefore, performance determination of meter slippage is a significant factor. One can estimate slippage from slippage quantity:

$$q_s = k \cdot \frac{dp \cdot w_c^3}{\mu \cdot l_c} \qquad \text{(IV/1.4.1-1)}$$

where dp = differential pressure; w_c = clearance width; l_c = clearance length; k = unit constant; and μ = absolute viscosity of fluid.

Now let us look at the factors affecting slippage.

1. **Flow rate:** The flow rate changes due to a change in the differential pressure when internal frictional resistance and viscosity change.
2. **Viscosity:** When viscosity increases the flowability naturally decreases, making it difficult to pass through the clearances of the measuring element and static casing. Because of this it is often said that high-viscosity fluids act as sealants for PD meters.
3. **Friction:** It is obvious that as the friction increases then more differential pressure will be required to cause slippage. When friction is plotted against flow rate it is found that at nearly 50% flow, slippage will be lower than that at 100%. This is also explained in the following subsection. If the percentage of slippage is not lower at 50% of flow rate than at 100%, there is probably abnormally high mechanical friction [4].

4. **Wear:** With wear of parts there will be a change in slippage. For minimal wear in parts there could be a significant change in slippage, therefore wear is a very important cause of slippage.

1.4.3 PERFORMANCE CRITERIA FOR PD METERS

From the above discussions it is clear that performance of the meter is affected by both issues. This is clearly shown in Fig. IV/1.4.0-1.

Also, from the above discussions above it is clear that slippage is greatly influenced by flow rate and resistance to flow. These two factors are in opposition. Therefore, a combined effect will give the slippage curve with respect to the flow rate. This is shown in Fig. IV/1.4.0-2.

1. **Error and accuracy:** Now it is time to concentrate on the issue of slippage. For general discussions, wear can be set aside because it is pertinent to particular situations and not a generalized situation, and so, the remaining factors, i.e., flow rate, viscosity, and friction are the contributing factors. As the flow rate increases the chances of slippage increase on account of the higher differential pressure across the measuring element. In contrast, when resistance in the form of friction or viscosity increases, there will be higher resistance to flow, and hence slippage. Thus in Fig. IV/1.4.0-2 one can see that percentage of slippage increases with flow and the percentage of slippage decreases with increase in resistance. As a result of this the combined curve shows a minimum point somewhere near midway of the percentage flow rate. From this discussion it is clear that slippage is a function of flow rate and resistance, mainly viscosity. As the slippage increases the unaccounted-for flow increases, and hence more error and inaccuracy take place. Therefore one can infer that accuracy in the PD meter is a function of both the flow rate and resistance, i.e., mainly viscosity. During subsequent discussions on specific meters, these are shown through illustrations. Also, as the slippage increases there will be a greater measurement error and accuracy will fall. However, in the case of PD meters it is always advisable to consult the

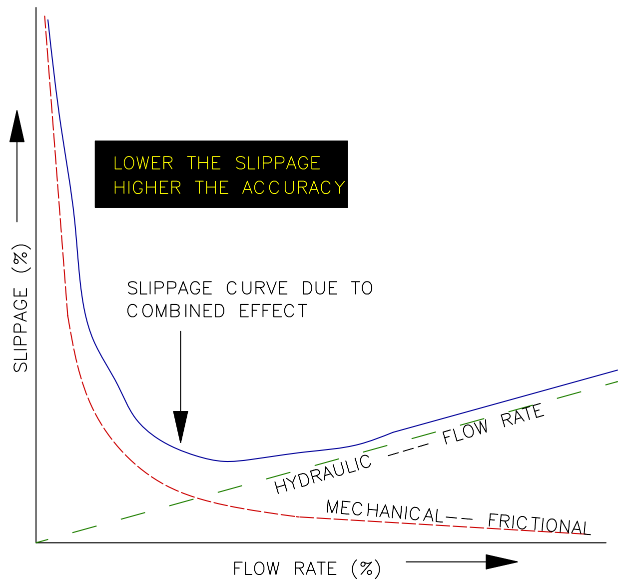

FIGURE IV/1.4.0-2 Slippage (accuracy) variations in PD meters.

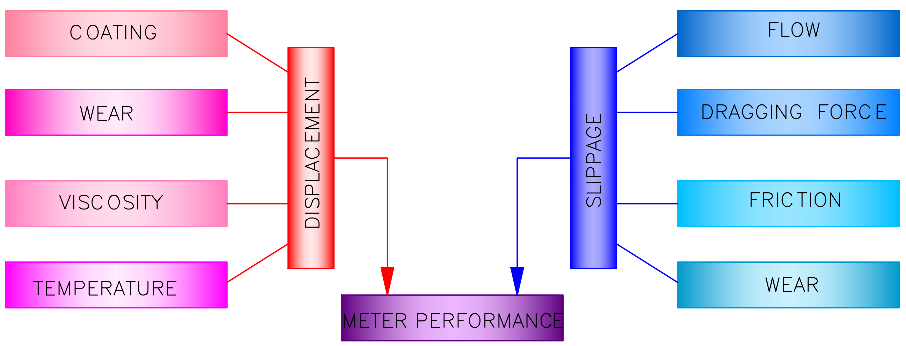

FIGURE IV/1.4.0-1 Factors for PD meter performance.

TABLE IV/1.4.3-1 Changes of Turndown Ratio With Viscosity

Viscosity (cP)	Flow Turndown Ratio (FTR)		Measurement Turndown Ratio(MTR)	
	Linearity 0.15%	Linearity 0.25%	Linearity 0.15%	Linearity 0.25%
0.5–0.8	5:1	10:1	8:1	16:1
0.8–2.0	8:1	20:1	20:1	50:1
2.0–5.0	15:1	25:1	40:1	60:1
5.0–20.0	20:1	35:1	80:1	140:1
20.0–100.0	30:1	50:1	150:1	250:1
100.0–400.0	50:1	75:1	200:1	300:1

Based on A Comparison of Liquid Petroleum Meters for custody Transfer Measurement, General Metering, Technical Paper, FMC Technologies, Issue/Rev. 0.0 (3/05), Bulletin TP0A014. http://info.smithmeter.com/literature/docs/tp0a014.pdf. Data from a Smith meter: Courtesy: FMC Technologies—Smith meter.

manufacturer's data sheet for accuracy and possible ways and means to improve the this, especially for electronic meters (where some scope for more linearization is possible).

2. **Meter and flow range:** Another interesting feature of PD meters needs attention. This is that viscosity meters are more stable in the medium- to high-viscosity range, which is one of the reasons why PD meters are preferred in measurement of fluids with more viscosity. For this reason, despite being older technology it still shares a good percentage of the flow meter market (especially in petroleum product flow measurement) after competing with newer technology meters. According to FMC technology Smith meters "Even though PD meters are the oldest custody transfer measurement technology, they are considered the best technology for many applications where accuracy, stability and reliability are required" [5]. If one looks at Eq. IV/1.4.1-1, it can be seen that viscosity μ is at the denominator meaning that the percentage of slippage will decrease with an increase in viscosity μ and the meter becomes linear for a wider range. Also, the higher the accuracy, the lower will be the flow span/measurement range turndown ratio. A typical table [5] is presented as Table IV/1.4.3-1.

From the table it can be seen that from each viscosity range, the viscosity turndown ratio (VTR) can be found, i.e., for the last row (100–400), VTR = 4. If one looks very closely at the table one can see that **MTR = FTR·VTR,** e.g., in the last row VTR = 4, FTR @ linearity 0.15 = 50:1, so MTR = 50 × 4 = 200, i.e., MTR is 200:1.

1.5.0 Applications and Selection of PD Meters

Although PD meter technology is very old it still finds applications in a wide range of flow measurement applications. A few major application areas for PD meters are highlighted below.

1.5.1 MAJOR APPLICATION AREAS FOR PD METERS

Starting from simple water flow measurement to custody transfer applications, there are many application areas for PD meters. Major areas of application are highlighted below:

1. **High viscosity low-flow applications:** New-technology meters have created stiff competition for positive displacement meters in some application segments. However, PD meters still remain the best solution for certain

applications, especially in low-flow applications and for measurement of flow in high-viscosity liquids.

2. **Utility billing:** Positive displacement flow meters have been taken for granted in a few application areas, such as billing applications for both water and gas. In utility applications, positive displacement meters are used extensively. Such applications include metering in residential, commercial, and industrial applications.
3. **Gas applications:** In gas applications, PD meters face competition from turbine meters, yet these are considered to be better solutions for flow measurement in smaller line sizes in the range of 40–300 mm. Also, on account of technological improvements in PD gas flow meters, smaller and lighter rotary PD meters are replacing the older-style diaphragm meters.
4. **Miscellaneous industrial usage:** PD meters enjoy specific applications such as measurement of crude oils containing paraffin wax, which are quite problematic for measurement with other types of meters. PD meters are also used extensively for biofuel handling, and have found applications in food processing plants and automobile plants.
5. **Oil and petroleum:** As discussed earlier, positive displacement meters in oil and petroleum applications are always preferred, including but not limited to the following:
   - Mobile unloading;
   - Unloading;
   - Loading;
   - Blending (e.g., sequential, ratio);
   - Normal metering (e.g., boiler application);
   - Custody transfer.

Every application has unique requirements to provide the most accurate measurements. There are a number of kinds/types of positive flow meters. Therefore, based on the intended application, it is necessary to select the proper type of positive displacement meter. In the following subsection short discussions are presented on selection methods for positive displacement flow meters in different applications.

1.5.2 SELECTION GUIDELINES FOR PD METERS

There are several types of positive displacement flow meters discussed in subsequent subsections. Like any other flow meter selections discussed at length in Section 4.0.0 in Chapter I, for PD meters one also needs to consider the product characteristics to marry with the system conditions to get the best performance. The following are the major points to be considered as guidelines for selecting an appropriate PD flow meter for the particular process application.

1. **Fluid type:** Since PD meters for air/gas applications are not the same for liquid, it is necessary to first consider whether the fluid in question is gas or liquid.
2. **Flow rate and turndown ratio:** The minimum and maximum expected flow rates of the system are very important considerations for flow meter selection. Flow rate and turndown ratio are dictated by process fluid (liquid) viscosity, the desired meter configuration, the pumping capabilities of the system and piping configuration. In this connection, Table IV/1.4.3-1 may be referenced. It is important to note that the FTR of the meter is derived from the MTR of the meter for the given linearity and VTR (allowable).
3. **Process condition:** Pressure and temperature, i.e., system conditions, play a major role in selecting the PD meter for any particular application.
   - *Pressure:* The pressure rating of the selected meter must be higher than the system pressure, otherwise there could be seal leakage or rupture of the casting.
   - *Temperature condition:* The temperature condition has multiple effects on meter selection. The higher the pressure, the greater will be the pressure derating factor casting. Also, temperature greatly influences the meter seal. Increased temperature will have a greater effect on corrosion of material. Temperature also

affects the mechanical registration of flow in the registering device.

4. **Pipe size:** As stated earlier, PD meters follow a square law in meter size. PD meters are suitable for lower meter sizes. Therefore, pipe size plays an important consideration for PD meter selection. Additionally, the piping configuration also important for PD meter selection.
5. **Pressure loss:** Pressure loss in positive displacement meters is high and increases with increases in flow rate. Sometimes positive displacement meters are used with additional accessories, such as air eliminator, valve, etc. to create greater pressure loss in the system. Also, from Chapter I it has been seen that the higher the viscosity, the greater will be the pressure loss in the system, meaning that sometimes it is necessary to reduce the flow rate to match the desired pressure loss allowed. Therefore, for PD meter selection this is fairly important.
6. **Material considerations:** The basic physical and chemical characteristics of the process fluid/product, such as viscosity, lubricating quality, specific gravity, chemical properties including any contamination and air/water content must be specified. It is necessary to select the product based on the construction material so that the PD meter is suitable for the process fluid intended to be measured and that the pH of the process fluid does not have an adverse effect on the chosen product materials. For process fluids with higher viscosity and lubricating property, PD meters are preferred. Materials incompatible with the product will potentially reduce accuracy, operation life, contaminate the liquid, and may be harmful to others [3].
7. **Viscosity:** It has been established in Chapter I that Newtonian fluids have viscosity to resist flow. Petroleum products and water show such a property. Normally positive displacement flow meters are capable of handling highly viscous fluids. However, it is necessary to check with the allowed viscosity for the meter in the product manual and also its suitability for the application. In the case of PD meters the viscosity range (like the flow range) is specified along with the associated linearity, as explained in Table IV/1.4.3-1.
8. **Lubrication:** In positive displacement flow meters the fluid comes directly into contact with moving parts. The lubricity of the process fluid plays a major role in determining the bearing materials. In the case that the process fluid has good lubricity it helps in dissipating heat between two metal surfaces, but if the lubricity of the fluid is weak, then it is necessary to choose meters with graphite and Teflon as bearing materials.
9. **Foreign materials:** It was earlier stated that positive displacement meters are suitable for clean fluids. Therefore, if the product/process fluid to be measured has foreign materials then these must be filtered. For this a strainer of suitable size is required to be place in the upstream side of the meter. Normally a 40-μm mesh screen is suitable for petroleum products and a 100-μm screen is used for liquefied petroleum gas (LPG) [3].
10. **Suspended materials:** Product/process fluids with soft products or with a low percentage of suspended solids will determine the required clearance rotors and/or bearings so that they do not have an abrasive effect on the meter. On account of machining tolerances in PD meters, any solids larger than the specified size could even stop the flow and may even damage the meter. Therefore, no hard solids or suspended solids $>5\%$ is recommended.
11. **Additional process fluid property:** There are a few materials that crystallize at high temperatures or when they come into contact with air, so when selecting the meter due consideration must be given to this, including the use of air eliminators.
12. **Housing/casing:** The housing/casing can be of single-casing or double-casing design. In

the former, as the name suggests, it is the pressure vessel as well as measuring chamber. On the other hand, in the case of the double-case type design, the measuring chamber is surrounded by a separate external housing. This offers the advantage of eliminating the pressure differential across the measuring element. Also, in this design, it is possible to carry out a hydro-test by measuring the element/line flush or serving [4]. When there is a fluctuation in the line pressure or changes in line pressure in the single-case design it may affect the accuracy of the meter. The housing contains the inlet and outlet so process connection is important.

13. **Process connections:** Depending on the line size and process condition, process connections at the inlet and outlet vary. Meters can be as small as 6 mm to as large as 300 mm (even 400 mm). Naturally the process connections may be G ¼″ to, e.g., G ¾″ or they could be ¼″ to, e.g., ¾″ NPT or BSP. Screwed connections or flange connections conform to international standards such as ANSI/DIN standards.
14. **Measuring chamber and measuring element:** Flow-measuring elements are housed in a chamber called the measuring chamber. There are basically two functions of measuring elements:
    - Separating the flow stream into discrete volumetric segments within the measuring chamber;
    - Absorbing energy from the flowing stream to drive flow meter components to register flow and overcome internal friction.
15. **Totalizing:** Positive displacement meters are also known as volumetric totalizing meters. Therefore, it is necessary to determine the requirement for local mechanical totalizing issues. Meters deployed for utility services, for example, in domestic applications, normally have a local totalizer for billing purposes. In some applications it is necessary to have an electronic remote transmission facility. Also, in some applications, e.g., boiler fuel flow applications, there is requirement for both local totalizing and remote transmission facilities. Therefore, while selecting a positive displacement meter it is necessary to determine these requirements beforehand and to select the meter accordingly. There are some variations in totalizing types.
    - *Mechanical type:* Meters may have direct mechanical counters to indicate the true volume. In the case of mechanical counters there is normally a calibration unit built in to make fine adjustments for variations in liquid properties and to compensate for manufacturing errors. Such adjustments normally address the revolutions through gear trains.
    - *Electronic type:* Most of instruments now have magnetic/hall and/or other types of sensors so that the flow information coming from the measuring element is converted into a precise ratio of pulses per volume. These electronic counter parts are mostly programmable digital electronics meaning a separate calibrator unit is not needed. Programmable electronics can be programmed to make any needed adjustments. In such cases a power supply is necessary, and for remote situations battery-operated versions are available.
16. **Remote transmission:** As stated earlier, in some applications there is a necessity for a remote transmission facility e.g., boiler application, pipeline projects, batch controlling, etc. Depending on the application, such signals could be pulse-type output (commonly available) and/or 4−20 mADC analog output. In modern systems many PD meters are available with digital communication facilities, such as HART protocol and/or with fieldbus (e.g., Profibus).
17. **Accuracy:** as seen from the discussions in Subsection 1.4.3, the accuracy of the meter is mainly determined from the flow range and viscosity range for which the meter will be deployed.

1.6.0 Types of Positive Displacement Meters

Based on the principles of operation there are various types of positive displacement flow meters. The working principles of these have already been discussed in Section 3.1.2 of Chapter I as well as at the initial part of this chapter, so these are not repeated here. The major types covered include the following:

1. Nutating disc;
2. Oval gear;
3. Rotating piston;
4. Rotating vane;
5. Reciprocating piston;
6. Lobed impeller;
7. Helical gear;
8. Gear PD meter.

There are a few other types, such as bi/tri rotor PD meters, which are similar to those described above. Some advantage and disadvantages of selected types are listed below in Table IV/1.6.0-1.

Short discussions are now presented on some general practical issues associated with positive displacement flow meters.

1.7.0 General Practical Issues With PD Meters

Some of the general issues associated with PD meters are discussed below. These are mainly related to the calibration, installation, and commissioning of PD meters.

1.7.1 CALIBRATION ISSUES FOR PD METERS

The discussions presented below may be read in conjunction with Section 6.2.0 of Chapter I. While discussing the calibration of PD meters the most important issue is the meter prover.

1. **General:** Each flow meter is individually calibrated at the factory and then supplied with a calibration certificate giving the K factor (see Subsection 6.2.1.5 of Chapter I) or the number of pulses per unit volume (for a pulse output meter) as well as the error value. Normally, at the factory, either water or factory calibrations using the master meter method are carried out, using Castrol Diesel Calibration Fluid 4113 [6]. As long as the viscosity of the liquid to be measured is in that range, the

TABLE IV/1.6.0-1 Advantages and Disadvantages of Various PD Meters

PD Meter Type	Advantages	Disadvantages
Nutating disc	**1.** Wide variety of construction materials **2.** Good accuracy and repeatability	**1.** Accuracy falls when the viscosity of flowing fluid is less than designed for
Oval gear	**1.** High accuracy and repeatability **2.** Good for viscous flow and unaffected by change in viscosity **3.** Cost-effective **4.** Less prone to maintenance needs	**1.** Selected construction materials **2.** Not that good for water-based fluids
Rotating type	**1.** High accuracy and repeatability **2.** Wide choice of construction materials **3.** Sweeping action prevents build up of sediment and keeps meter clean **4.** Low pressure drop	**1.** Complexity in design
Reciprocating type	**1.** High accuracy and repeatability **2.** Wide choice of construction materials, especially suitable for food applications **3.** Single moving part for wear	**1.** Suitable for very clean liquids

meter can be used without loss of flow meter performance when using the factory calibration. For other liquids, it is necessary to recalibrate the flow meter on the liquid that will be measured. For any meter field calibration, it is important to consider the accuracy of the calibration procedure. The calibration procedure should be run for at least 2 min in order to reduce the impact of startup and shutdown flows [6]. Scale and master meter methods are used; of these master meters are more popular for PD meter calibration from an accuracy and practical point of view. The calibration method and devices must be traceable, as discussed in Subsection 6.2.1.6 of Chapter I.

2. **Meter prover:** The volumetric meter prover generally refers to filling up a tank of known volume at various flow rates. For each flow rate there should be multiple proving runs, so that better linearity and repeatability are well established. Volumetric provers can be taken as the primary standard when the same is done at a specified pressure and temperature to obtain the true volume. The following issues should be taken into account to get the proper base volume:
   - *Accurate prover:* The testing prover is a scientifically designed means of testing. It should have a proper built-in drainage system and calibration gauge glass neck. The *capacity* of the prover should be at least 1 min flow volume through the meter at the maximum capacity of the flow meter in question. Provers must have a set level to repeat tests. There should also be protection against deformation (so as to ensure no volume change). These provers should be checked periodically for accuracy and to ensure they were not damaged during previous use, storage, or transportation.
   - *Discharge:* When a portable prover is used, the discharge from the meter should be normal and the same as that used for the meter.
   - *Wetting the prover and testing:* When a prover is filled in, the amount it can drain is its capacity. So the amount that cling to dry internal surface is loss. Therefore wetting helps to minimize such loss. The accuracy of a prover is determined by the wet measure capacity of its manufacturer, and the procedure for wetting the prover recommended by the manufacturer should be followed. After wetting the prover the testing should be carried out.
   - *API recommendation:* From API recommendations it is found that prior to the prover running, the meter must be thermally stable.
   - *Temperature:* The meter is run for some time to ensure that it is at the same temperature as the process fluid.
   - *Place:* The meter should be closer to the volumetric prover so that there is no temperature difference. It is better to test it in its normal operating position, as opposed to a separate test stand.
   - *Temperature measurement:* Temperature at the prover and in the line adjacent to the meter must be measured.
   - *Pressure measurement:* The line pressure reading should also be taken.
3. **Master meter prover:** This is the same as any other meter, only it is checked, calibrated, and proven against one primary standard, such as API. The characteristics of the master prover are defined in the primary standard, e.g., API. The master can be used to test another meter, as long as they are at the same pressure and temperature; they should also be close to each other (under 50 m).
4. **Determination of test results and performance tests:** The National Institute of Standards and Technology, in its NIST Handbook 44 sets out the detailed procedure. The latest edition (at the time of writing the handbook is "Specifications, Tolerances, and Other Technical Requirements for

Weighing and Measuring Devices as adopted by the 101th National Conference on Weights and Measures 2016") of the handbook should always be followed for result determinations, performance determination tolerance, etc.

1.7.2 INSTALLATION ISSUES FOR PD METERS

From the above discussions it is clear that when PD meters are used in liquid applications, then the liquid should be free from air and clean. Also, on account of no straight length requirement, control valves can be used. Therefore, a number of accessories are normally used with PD meters.

1. **Accessories:** The major accessories for PD meters are:
   - Proper metering strainer with suitable mesh;
   - Air eliminator;
   - Control/shutoff valve.
2. **Strainer:** For proper operation of PD meters it is necessary to properly protect the meter by making sure that the liquid entering the meter is clean and free of foreign particles. Therefore a proper strainer should be used upstream of the meter. Some PD meters are supplied with an inlet strainer, e.g., the rotary vane PD meter. There are many kinds of strainers, e.g., the Y strainer. There are various sources of solid particles:
   - Dust settling in storage tanks;
   - Wear on pumps or mixers;
   - Pipe scaling;
   - Particles from cutting or welding.
3. **Air elimination:** Air bubbles or vapor in liquid will not only cause measurement errors but could cause serious damage to the flow meter. To get rid of air/vapor in liquid, an air eliminator is recommended at the upstream of the meter. Also for air elimination the following issues may be considered:
   - Pump feeding the line has flooded the suction;
   - No possibility of an air trap in the line.
4. **Piping and support:** The piping system should be clean in all respects and devoid of any dirt, rust, and pipe scale. The meter should be properly bolted/supported from the foundation and/or other structural support, along with proper support for all accessories and for the inlet/outlet also. It is important to ensure that PD meters are not subject to any stress or strain and can function freely.
5. **Accessory mounting:** Mounting of accessories and their requirements are elaborated on with some illustrations for some specific PD meters, such as the nutating disc, oval gear meter, etc. Depending on applicability these can be utilized for other PD meters also. Many of these PD meters are used to measure fuel in utilities and other boilers, and in such cases there may be the necessity to maintain a specific temperature for the fuel, e.g., Heavy fuel oil (HFO) or Low sulphur high speed (LSHS), so that the liquids have proper flowability at the same time as not being enough heated to cause a fire risk. Therefore, in such applications as boilers, special piping arrangements are necessary. This has been detailed in Fig. IV/2.4.0-3 (in connection with a nutating disc). Depending on applicability, the same arrangements may be considered for other PD meters also.

1.7.3 PRESSURE DROP

Pressure drop is an important issue for PD meters and there are various methods to calculate this. A nomograph may be used or another method, such as the manufacturer's specified curves. Different methods are discussed in connection with various PD meters in subsequent sections.

1.7.4 SOME IMPORTANT PD METER ISSUES

There are a few issues which need to be considered when using PD meters for any applications. These are some precautionary measures:

1. **Overspeed:** Overspeeding of the PD meter can cause it damage.

2. **Leakage:** Leakage can deteriorate the performance of the meter. Should leakage occur and there is also a change in temperature then the viscosity will change and this can further aggravate the situation.
3. **Energy loss:** As in PD meters, driving energy is taken from flowing fluid, so there will high pressure loss, which must be taken into consideration during design. As PD meters are like pumps, drives may be used to overcome the issue.
4. **Wear and tear:** As already discussed, the meter has many moving parts there will be a greater chance of wear and tear of components. Therefore it should not be used for abrasive liquids and proper filtering is necessary to ensure only clean liquid passes through the meter.

1.8.0 Positive Displacement Meter in Gas Applications

Positive displacement meters are more common in liquid applications, however, PD meters are also used to measure gas flow. Diaphragm meters, lobed impellers, and rotary vanes are common PD meters used in gas applications. The diaphragm meter is a common type of PD meter in gas applications. There are four chambers in the measurement section. These four chambers are formed by the volumes between the diaphragms and the center partition and between the diaphragms and the meter casing. The DP across the diaphragm extends into one side while contracting on the other side to cause filling and emptying of the four compartments in sequences that follow PD meter principles. There is a D type slide valve to control the process. The D slide valves work in synchrony with diaphragm motion. Other meter types are discussed in subsequent sections in this chapter. Dirt and moisture are the worst enemies of good meter performance for measurement of gas flow through PD meters and inlet filtering is very important [7]. In the following sections various types of PD meters are discussed at length.

1.9.0 Custody Transfer Applications

From the above discussions it is clear that PD meters measure the number of times that the container is filled and emptied to give an indication of fluid flow through the flow meter. In PD meters volume flow is divided into segments and each segment of fluid volume passing through the meter is counted to yield a measure of total volume. In most cases these meters do not require external power for operation of the meter. As stated above, they are frequently used for custody transfer applications, especially for oil and petroleum products with higher viscosity. Similarly, turbine flow meters (TFM)—discussed in Chapter V—are also used for custody transfer applications. If one recalls the working principles of a turbine flow meter (see Section 3.1.3 of Chapter I) it could be inferred that flow is measured in turbine meters by measuring the velocity of the fluid. Though both could be used for custody transfer applications with similar accuracies of 0.2% FSD, the major difference is that *PD meters* are used for viscosity > *10 cSt*, whereas *turbine flow meters* are used for viscosity <*10 cSt* (Table IV/1.9.0-1).

TABLE IV/1.9.0-1 Comparison of PD Meters and TFMs for Custody Transfer

Parameter	Positive Displacement Meter	Turbine Flow Meter
Accuracy	For custody transfer application +0.2% FSD available	
Viscosity	Generally >10 cSt	Generally <10 cSt
Fluid	Clean fluid upstream strainer	Clean fluid
Normal capacity	Less than TFM but in a higher and bulky construction	Higher compared to PD meters in comparatively lighter construction
External power	Not essential for operation	Necessary
Installation	Not always mandatory	Requires upstream/ downstream straight pipe length

General discussions on positive displacement flow meters end here, with the text now turning to specific issues pertinent to different types of common positive displacement flow meters.

2.0.0 NUTATING DISCS

Nutating disc positive displacement flow meters can be deployed for measurement of ultralow flow rates to high flow rates. Normally, nutating discs are available up to 50 mm NB size. The basic working principles of nutating discs are described in Subsection 3.1.2.1 of Chapter I. The discussions on Nutating disc start as a continuation from Subsection 3.1.2.1 of Chapter I.

2.1.0 Descriptive Details of Nutating Discs

In this section a short recap of the measuring principles and description of nutating discs is given.

2.1.1 MEASUREMENT PRINCIPLES OF NUTATING DISCS

As discussed in Section 3.1.2.1 of Chapter I, entering through the inlet, liquid passes upward into the top of the main casing, where it submerges and lubricates the internal gearing and moves downward to the measuring chamber and, finally, liquid is discharged through the meter outlet. Following the principles of a PD meter, it is meant for continuous filling and discharging of the measuring chamber. The disc also divides the measuring chamber into compartments, two in the inlet side and two in the outlet side, to hold a defined volume of fluid. Liquid entering the measuring chamber drives the disc to nutate around the central ball which, in conjunction with the positive displacement cam and pressure differential, completes the cycle. The disc movements are transmitted with the help of a gear train. There will be magnetic (typical)/mechanical pick up for remote transmission. The edge of the flat portion of the nutating disc is thick. The liquid forms the seal between the disc and the chamber body. The bearings of the submerged gears carry the weight of the gears on the tops of the gear posts, forming an enclosed, dirt-proof construction. The amount displaced by a single movement of the disc remains constant for any specified liquid [8].

2.1.2 DESCRIPTION AND PARTS OF NUTATING DISCS

This discussion starts with reference to Fig. I/3.1.2-1. As shown in the figure the nutating disc flow meter consists of:

1. Meter casing;
2. Measuring chamber (with hole at the top);
3. One disc which nutates;
4. Central ball;
5. Submerged bearing;
6. Inlet/outlet port;
7. Shaft/mounting piston;
8. cam assembly;
9. Gear train;
10. Magnetic (or mechanical) pick up;
11. Miscellaneous items, e.g., process connection, electrical connections gasket, etc.

All these parts are made of materials suitable for the application. Meters are available at various sizes to measure an ultralow flow rate up to 400 GPM (>1800 LPM) with meter sizes starting from 12 mm NB (screwed) to 100 mm NB (flanged). Bronze, SS 316, and plastics are commonly used housing materials. However, other corrosion-resistant materials are also available. An accuracy of up to 0.2% FSD or better is available from the meter. It can withstand temperatures as high as ~200°C and ~22 kg/cm^2 pressure.

2.1.3 SIZING AND SELECTION OF NUTATING DISCS

Nutating discs are used for water flow measurements as well as for measurements of flow of oil and petroleum products which have wide

viscosity ranges. Therefore, it is necessary to specify the viscosity and other process conditions so that the meter can be sized by the manufacturers. Flow capacity is a function of viscosity. Therefore, manufacturers normally specify them in terms of the viscosity group. To specify viscosity it is necessary to consider the temperature. From the process data, the materials and viscosity group are assessed. Corresponding to the selected viscosity group suitable minimum and maximum flows are selected for the application. From the manufacturer's data the casing material and drive type are chosen based on viscosity group and associated flow meter range. It is worth noting that viscosity is often specified in terms of Saybolt Seconds Universal (SSU). SSU is basically dynamic viscosity, hence a function of specific gravity. When typically (approximately) specific gravity in the range $0.9 < \text{Specific gravity}$ @37.8°C < 1, SSU can be related to centipoises (which is the CGS unit of absolute viscosity equal to SI multiple millipascal seconds [mPa.s]) by the relation ***1 SSU ~ 0.216 cP***.

Typical data to specify has been illustrated in Table IV/2.1.2-1 [8].

Here a few things to be noted include that as the viscosity increases, the meter rangeability decreases. Also, for the same group there are two ranges, e.g., ranges 6 and 7 for group 2. This is due to variations in the available connection size, materials, and drive pick up options. For further details refer to Ref. [8]. From the material selection guide provided by the manufacturer it is possible to select materials for different components. There is a wide selection of ranges available for the register type desired.

2.1.4 PRESSURE DROP

The pressure drop through nutating discs is important issue. With an increase in viscosity, the pressure drop through the meter increases. Manufacturers provide pressure drop nomographs based on average testing (normally with water). Normally pressure drop is calculated or discovered in the following stages:

1. **Step 1:** In the first step the ***pressure drop factor*** corresponding to the viscosity of the process flow in the question is found from

TABLE IV/2.1.2-1 Specifying the Flow Capacity of a Nutating Disc

Group	1	2	3	4	5	6
Viscosity (SSU)	≤30	31–450	450–1K	1–5K	5.5–20K	20–50K
Range 1	0.75–5	0.5–7	0.2–5	0.2–5	0.2–3	
Range 2	1–11	1–20	1–15	1–8	1–4	
Range 3	3–18	2–30	3–20	1–12	1–6	0.5–4
Range 4	5–30	3–50	5–30	2–15	1–8	1–5
Range 5	7–35	5–100	7–50	2–35	2–20	1.5–10
Range 6	12–65	8–160	12–100	5–70	5–40	2–20
Range 7	18–100	8–240	15–125	9–80	9–45	4–25
Range 8	22–120	15–300	25–180	12–110	12–60	10–30
Range 9	35–180	20–400	30–250	16–190	16–100	14–50
Viscosity (cP)	0.2–1.0	1–90	90–220	220–1.1K	1.1–4.4K	4.4–11K

Flow ranges are given in gallons per minute (GPM—imperial) = 4.546 L/min (LPM).
Nutating Disc Meter Installation, Operation and Maintenance Manual, M110 Rev b, Niagara. http://www.controlswarehouse.net/pdf/niagara-nutating-disc-manual.pdf. Courtesy Niagara Meters.

the graph supplied by the manufacturer. It is necessary to multiply the pressure loss of the meter in the nomograph discussed below based on *water* as a flowing fluid.

2. **Step 2:** Manufacturers provide three suitable scales. The first scale represents the meter size, the second the flow rate, and the third scale gives the pressure loss. One needs to find the size in the first scale and the flow range in the second scale. A line is then drawn from the first point in the first scale to that in the second scale. This line is extended to intersect the third scale. This point at which this line intersects the third column is the pressure loss through the meter when measuring *water* [8]. Multiply the resulting viscosity pressure loss factor by the pressure loss obtained in the nomograph gives the actual pressure drop through the meter for the process fluid.

2.2.0 Features and Benefits of Nutating Discs

Nutating discs as a positive displacement flow meter enjoy a number of advantages and also a few limitations as listed below.

2.2.1 ADVANTAGES OF NUTATING DISCS

The following are the major advantages of using nutating discs:

1. As a positive displacement meter it does not require any external power and does not have any straight length requirements.
2. It is compact in design to save space.
3. It offers high accuracy, i.e., ±0.2% FSD.
4. It is capable of handling a wide range of viscosity (0.2 to 10^4 Centipoise).
5. High pressure/temperature and a wide variety of materials can be handled.
6. A variety of materials can be used in its construction.

2.2.2 MAJOR LIMITATION

Nutating discs are designed for a specific viscosity group, if there is a change from the designed one then there will be a deterioration in the accuracy.

2.3.0 Specification of Nutating Discs

A short specification for nutating discs is presented in Table IV/2.3.0-1.

TABLE IV/2.3.0-1 Nutating Disc Specification

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Liquid (say)*		*Also to specify fluid
2	Design pressure	E.g., 22 kg/cm^2 (max)		
3	Design temperature	E.g., 200°C		
4	Viscosity	To specify with temperature		
5	Registration	US/Imperial gallons/liters		To specify
6	Pick up type	Magnetic/mechanical		
7	Output	Pulse/4–20 mADC		
8	Output function	Mechanical totalizing/batch control/blending and batching, electromechanical totalizing, electronic totalizer, remote transmission		

Continued

TABLE IV/2.3.0-1 Nutating Disc Specification—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
Materials of Construction (MOC) for				
9	Casing	Bronze, CS, SS 316, epoxy coated iron		
10	Chamber			
11	Disc	Ryton		
12	Ball	Carbon, Ryton		
13	Gear	Bronze, SS		
14	Gasket	Nitrile, synthetic fiber, teflon		
15	Register	ABS, aluminum		
Connection and Mounting Details				
16	Process	½″ to 2 ½″ NPT, or 3″–4″ Flange		
17	Electrical	½″ NPT/ET		
18	Mounting	Horizontal		
Performance and Other Details				
19	Accuracy	±0.25–0.2%FSD		
20	Repeatability	<±0.2% FSD		
21	Certification	Necessary certification from appropriate authority for hazardous applications		
22	Application	Water/oil petroleum products		
23	Accessories	Rate flow and totalizing indicator, transmitter, batch controller, blending controller, valves, strainer		
24	Special feature	To specify		

2.4.0 Installation Details

In this section short discussions are presented on how nutating discs should be placed in the line and which accessories are to be provided. Such an installation would include the flow meter in the line where the flow is due to gravity. For general discussions Section 4.6.0 should be referred to. There are also major issues to be addressed when a meter is placed in a pump discharge and a special case when the meter is to be placed in a boiler installation. Each case is discussed in the following subsections. In all installations the nutating disc/flow meter must be in a horizontal line with the meter register in an upright position as shown in the figures in this section e.g. Fig. IV/2.4.0-1. The line should always be in a flooded condition so that there is no possibility of air in the line. In case there is any such possibility of entrapped air, then an air eliminator should be used. The dine should not be drained during usage. To install a flow meter, a strainer should normally be used in the line to ensure clean liquid.

2.4.1 FLOW METER IN GRAVITY PRESSURE INSTALLATION

Fig. IV/2.4.0-1 shows the flow due to gravity pressure with a flow meter installed.

In this figure a strainer has been used to eliminate any dirt in the line, i.e., to protect the meter from sediment and pipe scale. There should be a proper arrangement to clear the strainer easily and periodically. The flow meter is in horizontal line with the registering part in an upright position. To isolate the meter and/or strainer, isolating valves are used.

2.4.2 FLOW METER IN PUMP DISCHARGE INSTALLATIONS

When a nutating disc or similar flow meter is installed at the discharge line of a pump, it is necessary to ensure that there is no chance of air becoming entrapped in the line. In such cases air eliminators should be used in the line, as shown in Fig. IV/2.4.0-2. In the case that the suction of the

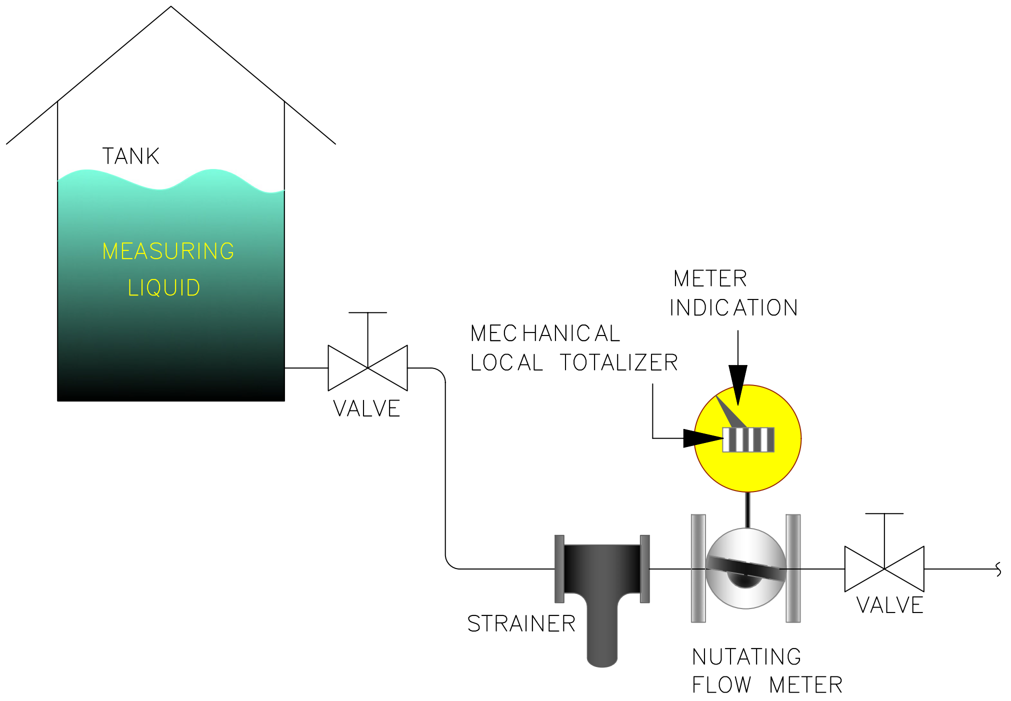

FIGURE IV/2.4.0-1 Nutating disc installation for gravity flow.

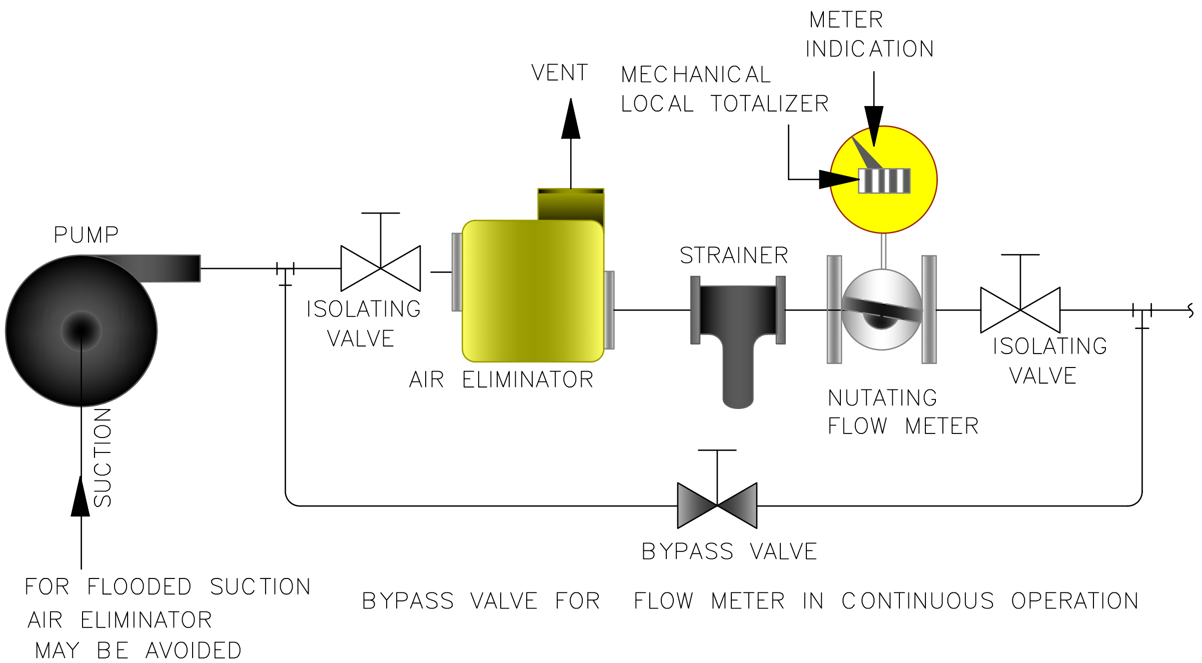

FIGURE IV/2.4.0-2 Nutating disc installation at pump discharge.

pump is flooded with liquid, then an air eliminator may not be necessary. For continuous operation, there should be one bypass line with a valve as shown in Fig. IV/2.4.0-2 to facilitate isolation of the meter and continuation of plant operation, etc.

2.4.3 FLOW METER IN UTILITY APPLICATIONS

There are a few oil and petroleum products, such as heavy fuel oil (HFO), which lose flowability at normal temperatures. Therefore, in order to maintain flowability, it is necessary to keep them heated. The tanks in which these are kept are heated by floor and suction heaters, and the line is heat traced. In such cases it is necessary to have constant circulation—through short and long recirculation lines. These are discussed in details in Ref. [9] and the interested reader is referred to: http://store.elsevier.com/Power-Plant-Instrumentation-and-Control-Handbook/Swapan-Basu/isbn-9780128011737/. Similarly, at the boiler front there are now return lines in the boiler front, as shown in detail in Fig. IV/2.4.0-3. Since there is a return line there will be two sets of meters; one in the supply line and one in the return line so that oil supplied to the boiler can be computed.

It should be noted that in both the return and supply lines, meters are provided with isolation valves and bypass lines with valves. This arrangement helps in maintaining the meters.

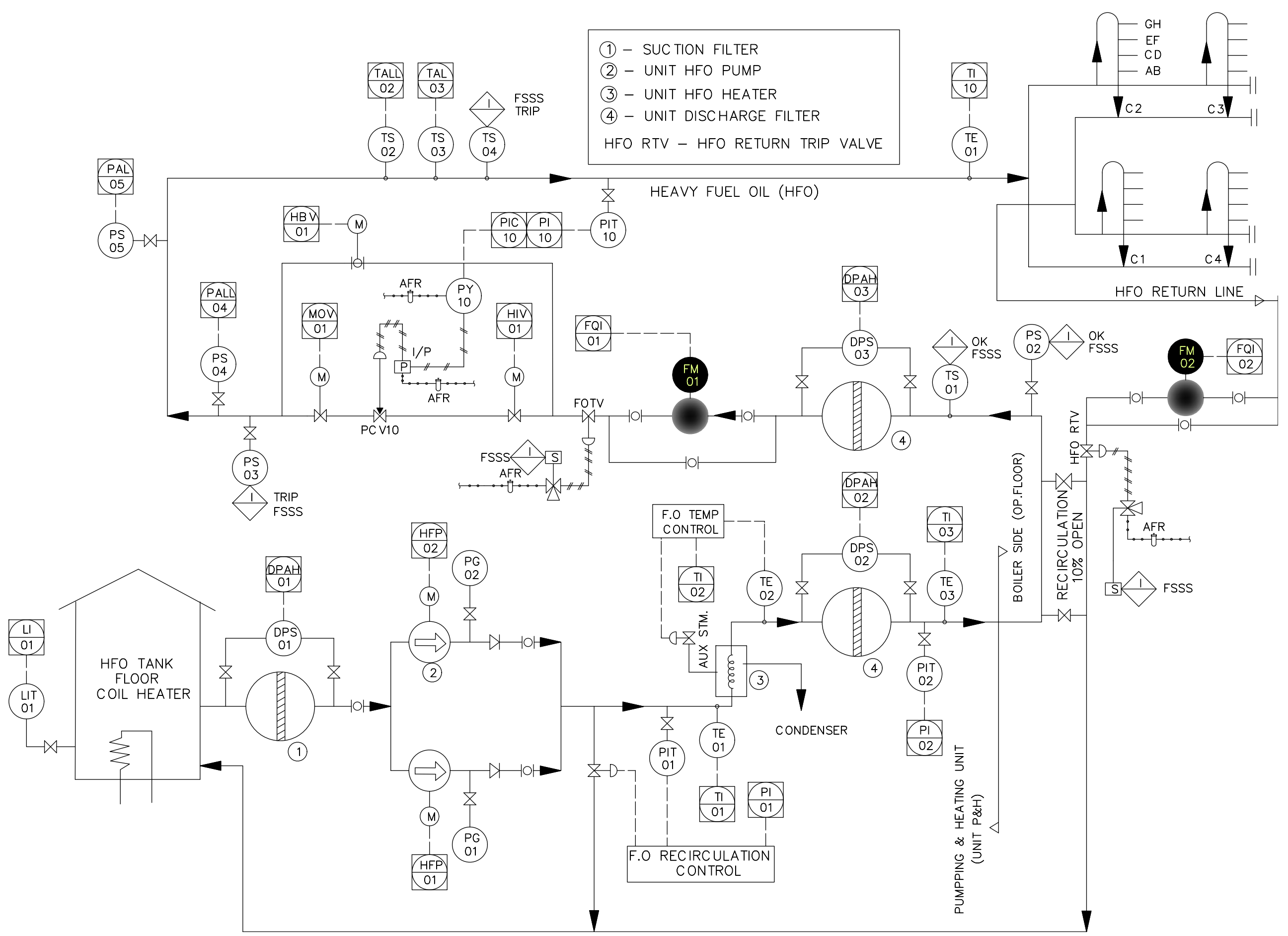

FIGURE IV/2.4.0-3 Flow meter in utility application. *Taken From S. Basu, A.K. Debnath, Power Plant Instrumentation and Control Handbook, Elsevier, November 2014. http://store.elsevier.com/Power-Plant-Instrumentation-and-Control-Handbook/Swapan-Basu/isbn-9780128011737/.*

Since there are suction and discharge strainers, separate strainers for meters may not be necessary. To ensure flowability and flooded suction there should also be suction heaters. The reader should note the return lines from the boiler and also recirculation for the pump.

3.0.0 OVAL GEAR

An oval-gear meter is a special rotating–lobe meter, where crescent-shaped gaps in the top and the bottom capture a fixed volume of liquid through the inlet, in stages and following PD meter principles, this volume of liquid is discharged to the outlet. Like a nutating disc it can also measure very low- to high-volume flow.

3.1.0 Description of a Oval Gear Meter

The discussions in this section start with recaps of the principles of operation (see Section 3.1.2.2 of Chapter I) and description details. There are some variations of oval gear meter, but here a generalized description is provided.

3.1.1 PRINCIPLES OF OPERATION

In an oval gear meter, two identical precision-molded oval gears, which mesh together by gear teeth around the gear perimeter are used (see the discussions in Subsection 3.1.2.2 of Chapter I). The gears rotate on stationary shafts fixed within the measuring chamber. This gear combination seals the inlet from the outlet and a precise volume of liquid is captured by a crescent-shaped gap, formed between the housing and the gear, as shown in Fig. I/3.1.2-2. This also causes a slight pressure differential across the meter, resulting in the movement of the oval gears. On account of the movement of the gear combination, fluid is carried to the outlet. Such movement also results in rotation of the output shaft through which the register operates. In the case of fluid with higher viscosity (>10 cP) and for high flow rates (>1 GPM) the leakage between the gear and housing is small and an accuracy of 0.1 actual reading is possible [7]. The variations in viscosity affect the accuracy, so that if a meter is calibrated with water then for higher viscous fluids it will be inaccurate.

3.1.2 DESCRIPTIVE DETAILS FOR OVAL GEAR METERS

Oval gear meters enjoy popularity on account of their simplicity in design and high performance in the field of applications. Oval gear meters are available in both screwed and flange type process connections of different international standards. However, flange connections are more popular across the range of applications. These meters are available in a wide range of sizes and flow capacity starting from 4 mm up to >350 mm sizes, with flow capacities from <1 L per hour to 20,000 LPM. They can handle pressures and temperatures up to PN100 and 300°C (from a renowned manufacturer) respectively. Meters with rating up to 400 bar are also available. Basically the meter consists of a meter body and oval rotor (gear) assembly complete with shaft. These are made of stainless steel (316SS). In addition to metal shafts, ceramic shafts are also available and used. However, rotors could be made of other materials such as aluminum/ryton. Bearings made from ceramic/carbon and seal made up of viton/EPDM/Nitril are also parts of the meter. An accuracy of 0.1% FSD is available. A general arrangement for an oval gear meter is shown in Fig. IV/3.1.2-1. This figure shows various options available for connections (such as screwed and flange connections of various international standards), as well as for register and remote transmissions. In most cases oval gears are offered with the local indication for total flow. There are local indications with both a selectable rate flow as well as a total flow. As accessories,

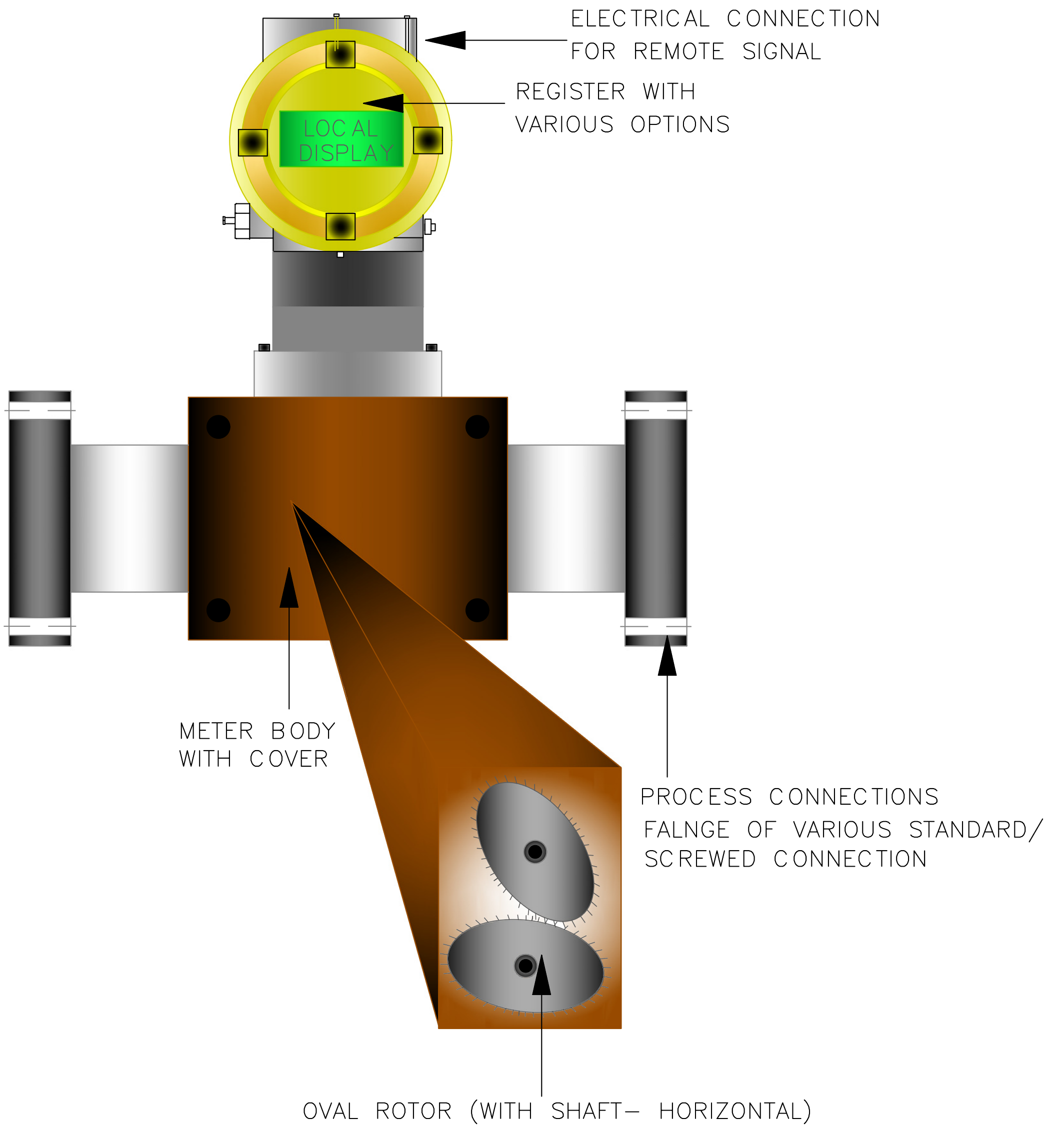

FIGURE IV/3.1.2-1 Oval gear general arrangement.

mechanical counters, *electronic counters*, *pulse pick ups*, *remote transmitters*, and *processing peripherals* are available.

Oval gear meters have both analog as well as pulse outputs.

3.1.3 PRESSURE LOSS

Pressure drop in oval gear meters is comparatively less than other systems, but is still important in system design. It is needless to tell that pressure losses are functions of the flow and viscosity of the fluid passing through the meter. In most cases flow versus pressure loss at different viscosity values are given in the catalog for various sizes of meter. Fig. IV/3.1.3-1 shows one such curve presented as pressure loss versus as a percentage of flow range at different viscosity values. Since flow is indicated in

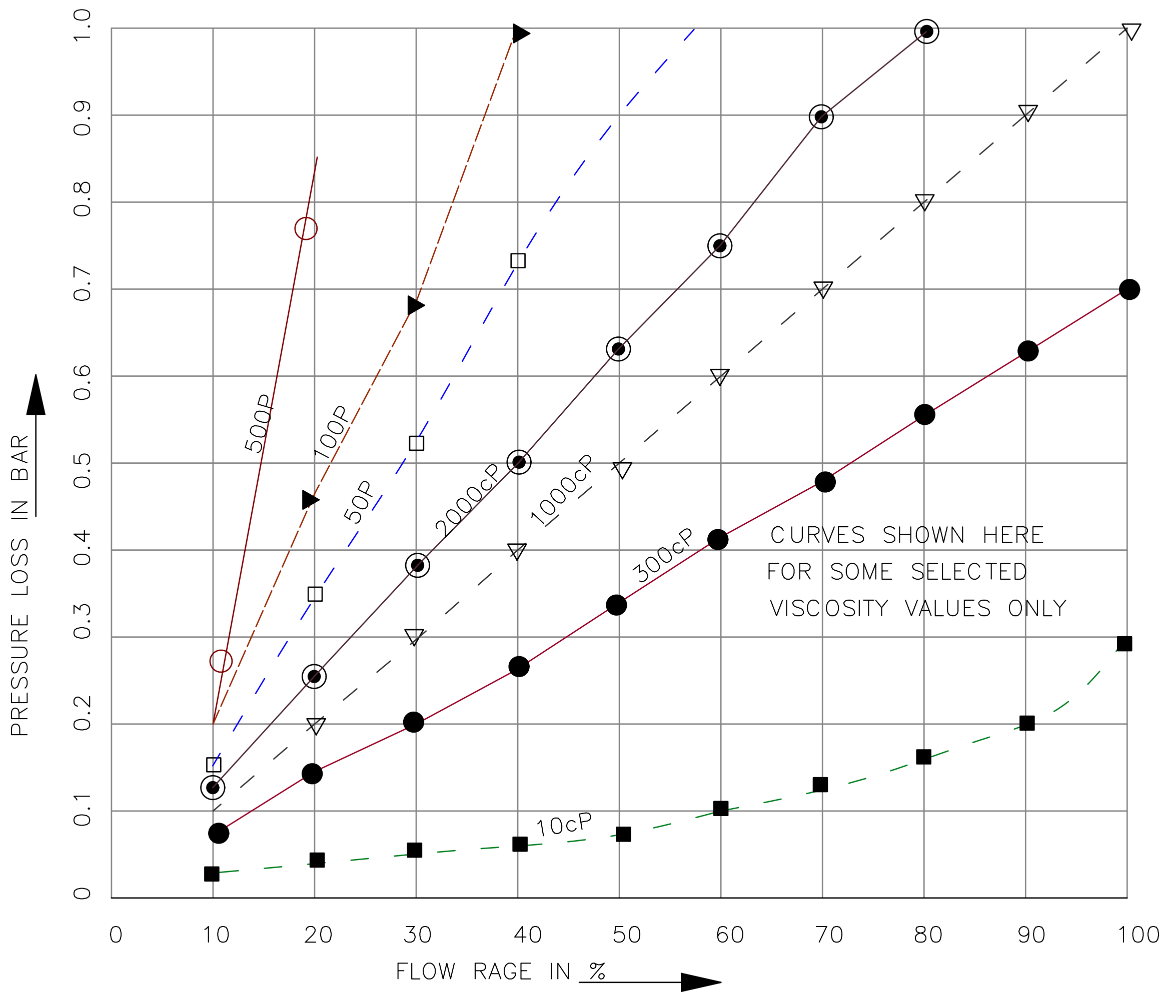

FIGURE IV/3.1.3-1 Pressure loss curve for OG meter.

percentage terms it is easier to fit the same for different sizes.

Various meter features are described in the following subsection.

3.2.0 Features and Benefits of Oval Gear Meters

Flow measurement technology by oval gear meters is not new. However, on account of their field-proven technology, they are still in use, however there have been a number of modifications in the meter design over the years. Now smart meters with HART and Fieldbus (e.g., Profibus) communication methods are available, making quick networking and integration easier. The advantages and limitations of oval meters are discussed in the following subsection.

3.2.1 MAJOR FEATURES AND ADVANTAGES

In line with other PD meters, oval gear meters do not have a straight pipe length requirement, as

already discussed. Some of the specific design features and benefits are enumerated below,

1. Proven and reliable oval gear technology;
2. Simple sturdy, compact, but rugged construction;
3. Higher rotor stability;
4. Excellent chemical resistance possible;
5. Available from miniaturized to high-flow versions;
6. High pressure, temperature, flow, and viscosity are supported;
7. Wide range of flow and viscosity are supported;
8. Enclosure IP67 or better available;
9. No requirement for flow conditioning;
10. Comparatively low pressure loss;
11. Individual calibration;
12. Variety of flow sensors (magnetic, Hall, Reed switch, NAMUR sensor);
13. Built-in compact pulse generator;
14. Various types of local displays (including touchscreen);
15. Rate and totalized flow at local display;
16. Variety of registers and batch controller;
17. Secondary electronics to support communication;
18. HART, fieldbus with 4–20 m ADC supported in smart sensors;
19. Comprehensive monitoring, control, and safety functions;
20. **Accuracy*:** ±0.7% AR for water and ~ ±0.1% AR for oil services;
21. **Repeatability*:** 0.1% AR.
    *The values given above are approximate values available from various manufacturers.

3.2.2 SOME LIMITATIONS OF OVAL GEAR METERS

Like other PD meters, oval gear meters also have a few limitations, as listed below:

1. Oval gear flow meters are not suitable for steam/slurry or multiphase fluids;
2. Accuracy is highly affected by slippage, which is a function of the flow rate, differential pressure, temperature, viscosity, and clearance, etc.;
3. It is mainly suitable to measure fluids with high viscosity, mainly from a slippage point of view;
4. Any presence of air/bubbles in the fluid adversely affects the accuracy and may damage the meter.

3.3.0 General Design Details

Short discussions on a few design issues are presented here. A detailed description of the mechanical parts has already been given in Section 3.1.2. Here some additional system design details about these meters are presented. Input and meter range have been discussed in Section 3.4.0.

3.3.1 ELECTRICAL SECTION

In this subsection electrical details along with output possibilities for oval gear are covered.

1. **Pick up, transducer, and transmitters:** Any oval gear meter with a smart transmitter consists of a pick up, transducer, and transmitters (which are now called *smart transmitters*):
   - *Pick up:* Used for signal detection, i.e., magnetic, Hall, Reed switch, Namur sensor;
   - *Transducer:* Measures the volume of liquid through the meter;
   - *Transmitter:* Electronic transmitter processes and evaluates the meter pulses to produce the required output in 4–20 mADC/HART and/or fieldbus signal as applicable.
2. **Output:** There could be a variety of outputs such as:
   - Pulse output;
   - Hard Wired 4–20 mADC;
   - HART;
   - Fieldbus, e.g., Profibus;
   - *Load:* There will be load of around 1000 Ω (varies with supply voltage).

3. **Electrical and safety data:** For meters with transmitters and pick ups there will be a supply voltage and there will be electrical and safety data specified by the manufacturers. These data include, but are not limited to: input/output voltage, amperage, internal and external inductance, and capacitance values. These are important values to noted in order to obtain the failsafe output as well as for the circuit with ignition protection meant especially for intrinsic safety circuits. There are variations in input voltage, amperage inductance, and capacitance when optical isolations are used. These require detailed discussions beyond the scope of this book. These data are normally specified by the manufacturer in the catalog. For detailed requirements and for developing the design basis for IS circuit design, Chapter X of Ref. [10] may be referenced where these are discussed at length.

3.3.2 ENVIRONMENTAL CONDITIONS

The majority of oval gear meters can withstand large environmental temperature variations. Normally they can be used in the temperature range of −10°C to 65°C. They can also withstand a high-humidity atmosphere. The guiding standard is IEC 60654-1. Normally these fall under Class D1 (IS 15294:2003 driven from IEC 654-1).

The conditions for D1 are (data taken from IS 15294:2003 driven from IEC 654-1): Temperature range of −25 to +70°C with humidity; 10 to 100% RH including condensation and direct wetness, and maximum water content in dry air 35 g/m^3.

However, in practice, flow meters offered by the manufacturers have smaller ranges.

The enclosure classes normally available for electrical protection are IP65/NEMA 4, however, IP67 enclosures are also available.

3.4.0 Meter Size, Selection, and Performance

In line with PD meter characteristics there is a variation in meter flow range, meter factor (K factor, i.e., the number of pulses/unit volume flow), and the performance, such as accuracy based on meter size in conjunction with the viscosity of the liquid flowing through the meter. In the following subsection, it can be seen that there could be different capacities for the same size of meter, e.g., size DN 25 has two capacities in the example discussed below.

3.4.1 METER SIZE AND RANGE SELECTION

As stated earlier, most meters cover a wide range of flows and viscosities. Like nutating discs, the flow ranges here are also based on two main

TABLE IV/3.4.1-1 Oval Gear Meter Measuring Range [11]

Size	Capacity	Viscosity	<0.3	0.3–1.5	1.5–150	150–350	350–1K	1k–3K
25	50	Min	8	5	5	2.5	1.25	0.45
25	50	Max	40	50	50	25	12.5	4.5
25	50	Cont	16	33	45	25	12.5	4.5
25	50	Batch	16	45	50	25	12.5	4.5
25	100	Min	16	10	10	7	3.5	1.2
25	100	Max	80	100	100	70	35	12

Continued

TABLE IV/3.4.1-1 Oval Gear Meter Measuring Range [11]—cont'd

Size	Capacity	Viscosity	<0.3	0.3–1.5	1.5–150	150–350	350–1K	1k–3K
25	100	Cont	33	66	90	70	35	12
25	100	Batch	33	90	100	70	35	12
50	300	Min	50	30	30	18	9	3
50	300	Max	250	300	300	180	90	30
50	300	Cont	100	200	300	180	90	30
50	300	Batch	100	270	300	180	90	30
100	3000	Min	400	250	250	200	150	75
100	3000	Max	2000	3000	3000	2500	1500	750
100	3000	Cont	800	1650	2500	2500	1500	750
100	3000	Batch	1000	3000	3000	2500	1500	750
200	8000	Min	1300	800	800	660	400	200
200	8000	Max	6500	8000	8000	6600	4000	2000
200	8000	Cont	2600	4000	5500	6600	4000	2000
200	8000	Batch	2600	5000	6600	6600	4000	2000
400	20,000	Min	3200	2000	2000	1500	1000	400
400	20,000	Max	16,000	20,000	20,000	15,000	10,000	4000
400	20,000	Cont	6600	10,000	13,500	15,000	10,000	4000
400	20,000	Batch	6600	10,000	15,000	15,000	10,000	4000

1 LPM = 0.06 m^3/h; cont, Continuous; Flow, LPM; Meter Size, DN; Viscosity, cP/mPa·s.
All data given here are courtesy of: Bopp & Ruether Oval Wheel Meter with Universal Smart Transmitter with HART® Communication, Series OaP, UST, Operating Manual, Bopp & Ruether, Messtechnik. http://doc.bopp-reuther.de/files/ovalradzaehler/A-EN-01222-I0.pdf (Part table).

factors: meter size and viscosity group. For each flow meter size there will be a given maximum flow capacity possible, e.g., a meter of size 50 mm may have a capacity of 300 LPM. However, for *each* viscosity group there will be minimum/maximum flow capacity supported. Also, there could be a variation in such capacity depending on the application/services, i.e., for continuous operation and/or batch processing. A typical such specification in tabular form is presented in Table IV/3.4.1-1.

3.4.2 METER PERFORMANCE AND K FACTOR

In this subsection, meter performance as a function of fluid type and associated viscosity, as well as meter K factor (see Subsection 6.2.1.5 of Chapter I) are discussed. The data given here are from a standard manufacturer.

1. Normally in custody transfer applications accuracy up to 0.1% AR is available. For normal meters an accuracy of 0.3–1% FSD is also seen. Such accuracy depends on the liquid and range of flow chosen. In the case of custody transfer, conformity with gaging regulations is also important. When one goes through the manufacturer's catalog variations in the level of accuracy are notable. Table IV/3.4.2-1 shows variations in accuracy of meters, with meter range and fluid types.
2. **Meter factor:** When meters are sent from the factory they are calibrated and the necessary

TABLE IV/3.4.2-1 Accuracy Variations for Oval Meters (Accuracy % FSD, Range LPM)

	Meter 1		Meter 2		Meter 3	
Liquid Type	Range	Accuracy	Range	Accuracy	Range	Accuracy
Oil	0.01–1	0.75	0.05–10	1%	0.5–100	0.5
Water	0.1–1	1%	0.5–10	0.5	4–100	0.75

certificates issued. In each case they mention the pulse count per liter and associated viscosity of the liquid for which it has been calibrated. For each meter there will be a specified K factor that indicates the number of pulses per liter. In Table IV/3.4.2-1, three - meters are used and the K factors for them are: Meter 1, K factor is *2050* pulse/L; Meter 2, K factor is *400* pulse/L; and for Meter 3, K factor is *70* pulse/L.

3.5.0 Specification of Oval Gear Meters

In this section a brief specification of oval gear meters has been presented as Table IV/3.5.0-1. The generalized data presented here are from reputed manufacturers, so they may differ from one particular manufacturer to another. Also, it should be noted that all these parameters are mainly the *highest* parameter available and *all are not applicable for each meter*.

TABLE IV/3.5.0-1 Specification of Oval Gear Meters

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Liquid in the application		
2	Design pressure	Max 100 bar		
3	Design temp.	300°C (Temperature)		
4	Viscosity	0.3 to 10^6 cP available		
5	Registration	In US/Imperial Gallon/L/m^3		Options available
6	Pick up type	Magnetic/Hall/Reed switch- Namur		
7	Output	Pulse, 4–20 mADC, HART, Fieldbus (e.g., Profi)		
8	Output function	Local rate, totalized display, remote transmission, batch control/register, communication		
Materials of Constructions (MOC)				
9	Casing/housing	Brass/cast iron, CrNi, Mo, hard carbon, stainless steel (316)		
10	Measuring chamber*	Brass/cast iron, hard carbon		*cover

Continued

TABLE IV/3.5.0-1 Specification of Oval Gear Meters—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
11	Rotor/wheel	Brass/cast iron/steel, CrNi Mo/SS 316		Rotor support: SS
12	Shaft	Stainless steel		
14	Gear	Carbon-filled PEEK		Refer to Fig. IV/3.5.0-1
15	Bearing	440C stainless steel/		
16	Seal	Viton/Nitril/EPDM		
17	Register	ABS		
Process Connections and Mounting				
18	Process	Mainly flanges of different sizes from DN15 to DN300. For smaller sizes screwed connection, e.g., ½″ to 2″ NPT		
19	Electrical	M20, ½″ NPT/BSP female		
20	Mounting	Horizontal as well as vertical		
Performance and Other Details				
21	Accuracy	+0.1%–0.75% AR*		*Variation with viscosity range
22	Repeatability	0.03%–0.1% AR		
23	Certification	Certification for safety applications		
24	Application	Major applications in high-viscosity fluids such as syrup, chemicals, oil, and petroleum/fuel including unloading, transfer and consumption monitoring, lubrication, automobile		
25	Accessories	Batch controller, totalizer, rate flow display, etc. In addition to mechanical accessories like strainer, etc.		
26	Special feature	To specify		

PEEK: PolyEtherEtherKetone; Basically Peek is a high performance, semi-crystalline, high temperature resistant, thermoplastic with many engineering usages. *PEEK* ***is often used with Carbon filled 30% with carbon fiber (30%) reinforced with PEEK****.* ***This is used for high compressive strength and stiffness with lower expansion rate.***

FIGURE IV/3.5.0-1 PEEK thermoplastic material.

3.6.0 Installation of Oval Gear Meters

Installation of oval gear meters is similar to other PD meters already discussed. For further details and general discussions, Section 4.6.0 should be referred to. However, a few points are to be noted for oval gear meters. The major issues here include, but are not limited to the following:

1. Normally oval gears are quite heavy so proper support is very important, especially for larger meters. Also pipe supports should be independent of the meter.
2. Proper orientation of the meter, so that the axes of the rotor shafts are always in the horizontal position.
3. When the meter has a local display/register, etc. these should be upright for proper viewing and if necessary the display unit may have to be rotated (rotating type).
4. Oval gear meter should be installed free from any strain.
5. Piping and other configurations, etc. should be such that any air admission is eliminated. Otherwise there will be not only deterioration of accuracy but there could also be unhealthy overspinning of the rotor.

In the following subsections, short discussions on the above issues are presented.

3.6.1 METER ORIENTATION

This discussion starts with Fig. IV/3.6.0-1A. These points should be followed.

1. The inlet and outlet ports should not be opened prior to the installation to prevent dirt ingress.
2. As applicable, when flow directions are mentioned (not applicable in the case of a bipolar pulse), they should be followed to orient the meter.
3. Meter orientation should be such that the axis of the rotor is always in a horizontal plane in all conditions, whether a horizontal or vertical pipe mounting as shown in Fig. IV/3.6.0-1A. This is important because if it is vertical then the weight of the rotor will be on the thrust bearing, causing a deterioration in the accuracy and, in the long term, it could damage the bearing and reduce the lifespan of the meter.
4. The housing cover will be in the vertical plane as shown.

3.6.2 PIPING CONFIGURATION

Fig. IV/3.6.0-1B and C are mainly related to the piping configuration. As is common with PD meters, oval meters should always be flooded with liquid, and air should be eliminated to avoid unhealthy overspinning of the rotor. Some of the issues include:

1. Prior to installing the meter in a pipe, the pipe must be cleaned and purged.
2. While installing a meter in the pipe line it is to be ensured that the process pressure and temperature are within the safety limits of the meter.
3. In the case of a meter with a bipolar pulse it is possible to measure flow in both directions but for other cases the meter must be fitted in the pipe as per the direction of flow indicated.
4. In the case of a vertical pipe mounting, flow should always be from bottom to the top, so as to ensure that the meter is always filled with liquid.
5. Oval gear meter installation at the pump suction should always be avoided, especially for large/medium-sized meters.
6. In the case that an oval gear meter placed at pump discharge, an air eliminator should be used to avoid air entering the meter. If the flooded section of the pump is ensured then the air eliminator may be dispensed of.
7. Strainers are used to supply clean liquid.
8. For continuous operation a bypass line to the meter is necessary, as shown in Fig. IV/3.6.0-1C. There should also be isolating valves upstream and downstream of the meter as shown. Such an installation

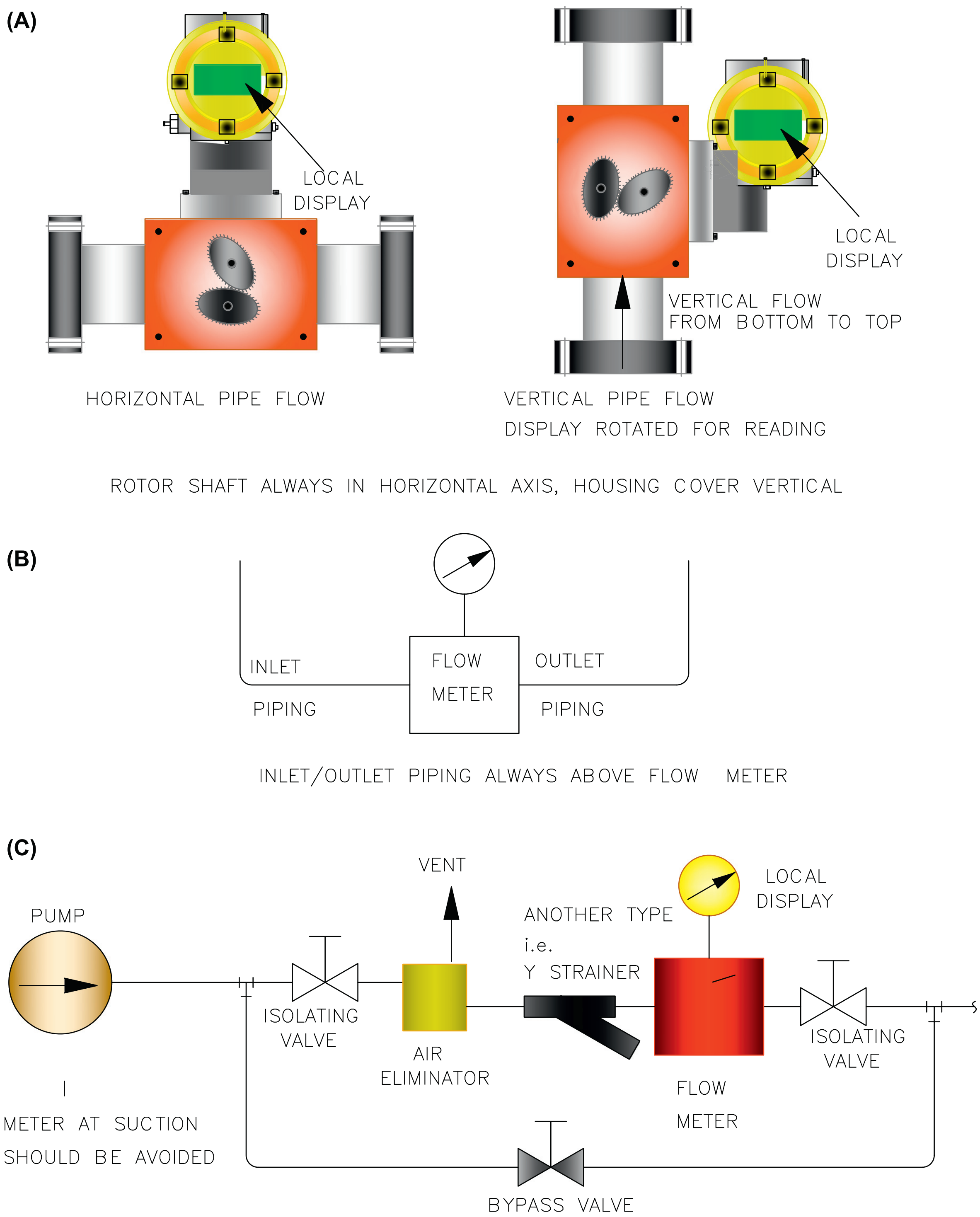

FIGURE IV/3.6.0-1 Oval gear meter installation. (A) Meter orientations. (B) Piping configuration. (C) Meter at pump discharge.

will help in keeping the process line on and at the same time ensure maintenance of meter by cleaning the strainer (here a Y strainer—another type of strainer than that shown for the nutating disc—has been shown for familiarization). In connection with this Subsection 2.4.2 may be referenced and compared.

9. The pipe surrounding the oval gear meter must be well supported, independent of the flow meter. For a larger meter size this is extremely important.
10. As shown in Fig. IV/3.6.0-1B the inlet and outlet piping of the meter shall be at a level higher than the meter to ensure that the meter is filled with liquid.
11. In controlled applications, the meter should be upstream of the regulator so that back pressure provided by the valve will be beneficial to system accuracy [6].
12. Oval gear meters are also used in utility stations for fuel measurements and in such cases the discussion in Section 2.4.3 and Fig. IV/2.4.0-3 are equally applicable here.

This conclude the discussions on oval gear meters to discuss Rotating piston meter—another type of PD meter.

4.0.0 ROTATING PISTON METERS

Of the various PD meters, rotating piston flow meters offer high performance in an economic manner. The flow meter is well suited for clean liquids with lubricating properties and viscous value in the range of 5 to almost 100 cSt.

4.1.0 Rotating Piston Flow Meter Description

This discussion starts with a recap of the operating principles of rotating piston meters.

4.1.1 PRINCIPLES OF OPERATION

The measurement chamber is cylindrical with a partition separating the inlet port from the outlet. Liquid enters into the measuring chamber from the inlet of the flow meter and this will cause a differential pressure across the piston, forcing the piston to rotate in the direction indicated by the arrow in Fig. I/3.1.2-3. This will enclose a volume of liquid, i.e., a crescent shape volumetric cavity will be formed as shown in the second and third figures in Fig. I/3.1.2-3. As the process of rotation continues due to the differential pressure, a portion of the enclosed volume will be exposed to the outlet. In this way, continuous rotation of the piston will cause liquid to pass through the flow meter. Thus with every cycle of the piston rotation an equal specified amount of liquid will pass through the flow meter. Therefore, by counting the number of rotations of the piston, the volume flow through the meter can be computed. The counting devices are completely isolated from the liquid and motivated by magnetic drive coupled magnetically with the piston. Therefore, the magnetic pick up counts the number of rotations and gives out the pulse output which, with the help of a converter, can be transmitted to a remote place in the form of 4−20 mADC.

4.1.2 DESCRIPTIVE DETAILS OF ROTATING PISTON METERS

A rotating piston flow meter, also referred to as oscillating rotating piston meter, consists of a housing and a rotating piston as shown in Fig. IV/4.1.2-1. Some meters are developed with a dual-casing design. Normally, the housing is made from stainless steel. Major components of an oscillating/rotating piston meter consist of:

- Housing, measuring chamber;
- Cylindrical piston;
- Axel;
- Guiding adapter;
- Baffle to separate the chamber;
- Cover plate;
- Magnetic drive assembly;
- *Process connection:* flange;
- Top display unit with adapter and electrical connector;
- Display unit rate/total;
- Pulse converter, etc.

The oscillating movement of the cylindrical piston is achieved in two ways. There is a vertical slot in the cylindrical piston, this slot accommodates a baffle/partition plate which is fixed to the chamber. The baffle plate prevents the piston from spinning around its central axis and acts as a seal between the inlet and outlet ports of the chamber [13]. Also, normally there is a center

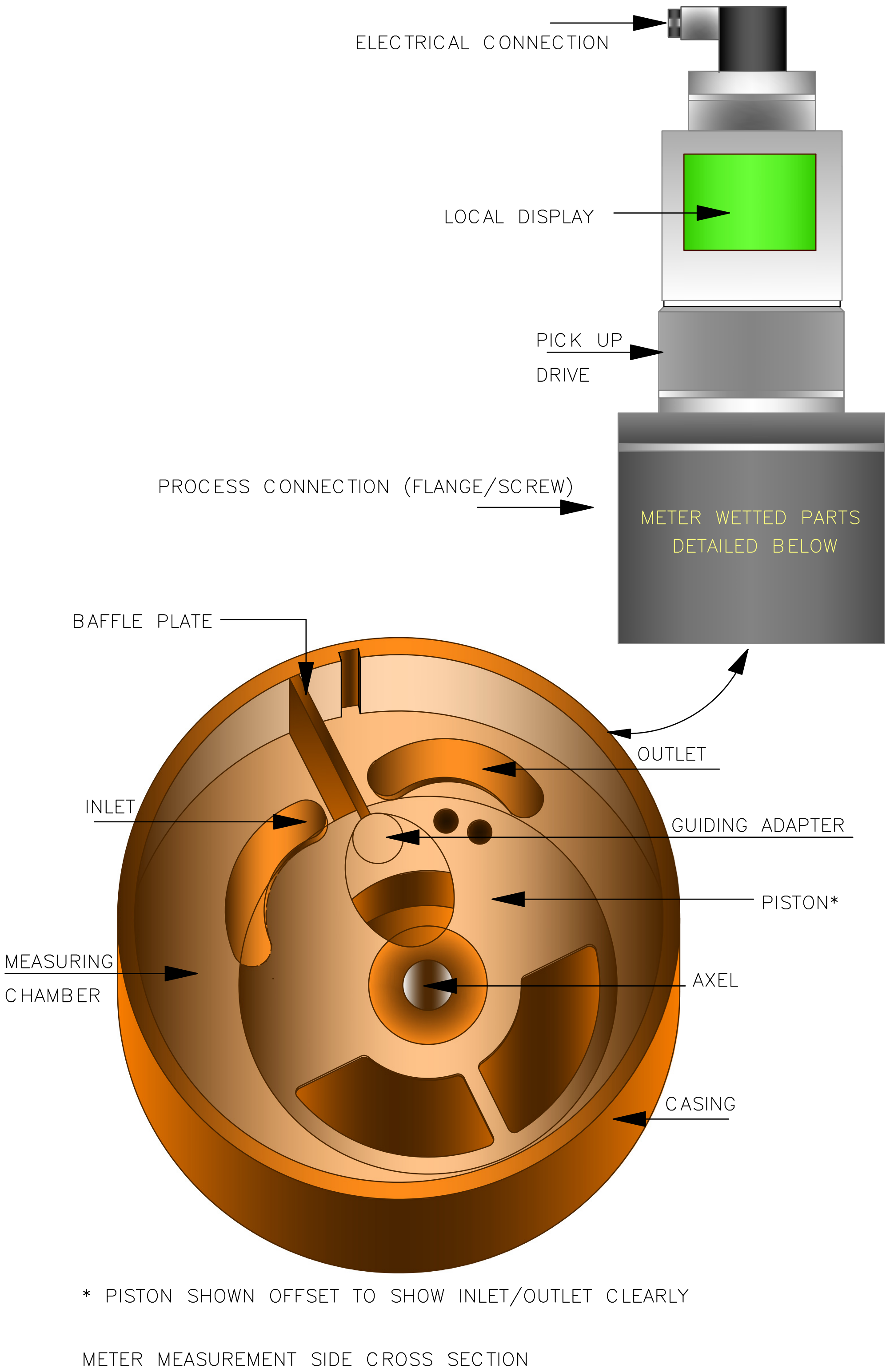

FIGURE IV/4.1.2-1 Rotating/oscillatory meter GA. *Based on Neptune Type Meter, Red Seal Measurement.* *http://www.redsealmeasurement.com/what-is-an-oscillating-piston-meter/. Neptune Flow Meter Courtesy: Redseal Measurement.*

vertical pin, also referred to as the guiding adapter, within to confine the piston's movement about the axel, i.e., the piston is guided by the guiding adapter in a circular/closed curved track/chamber at the bottom and top of the measuring body and with its slot at the baffle [14]. As shown in Fig. IV/4.1.2-1, the circular/closed curved track is a part of the oscillating/rotating piston, so as to ensure confinement of the piston's movement. Normally, during operation, the hydraulically floating piston does not contact the chamber surfaces. The inlet and outlet openings are located on the chamber's wall at both sides of the baffle plate and are sealed by the piston and the baffle. Different models are available from ¼″ to >3″ sizes, with different processes having flange or screwed connections. An accuracy of 0.5% AR is normal, but higher precision is seen of up to 0.1% AR. The majority of meters can withstand moderate pressure, however, a higher pressure rating up to 40 bar has also been noted. Some meters can withstand temperatures up to 80°C. Ambient temperatures of −10 to +60°C with humidity are also withstood by different models of meter.

These meters are designed for a specified range of viscosity and a moderate change in viscosity will not affect the accuracy. There are a variety of materials available for construction, as detailed in the specification sheet.

4.1.3 PRESSURE LOSS IN THE METER

Like other PD meters, rotating/oscillating piston flow meters also experience pressure loss as a function of flow and viscosity of the fluid passing through the meter. In this connection, Fig. IV/4.1.3-1 should be referred to. Variations in the pressure loss with flow have been shown for the larger meters on the left-hand side of this figure. On the other hand, variation in the pressure drop with viscosity is more prominent in smaller meters, as shown in the right-hand figure. The two different types of variation have been shown separately as most manufacturers offer them in this way.

In Fig. IV/4.1.3-1 both these situations have been depicted. In the first diagram it has been shown for 50 NB and 25 NB meters, where the flow range will be high, in the tune of 0−1200 LPM. Here pressure drop variations are more to

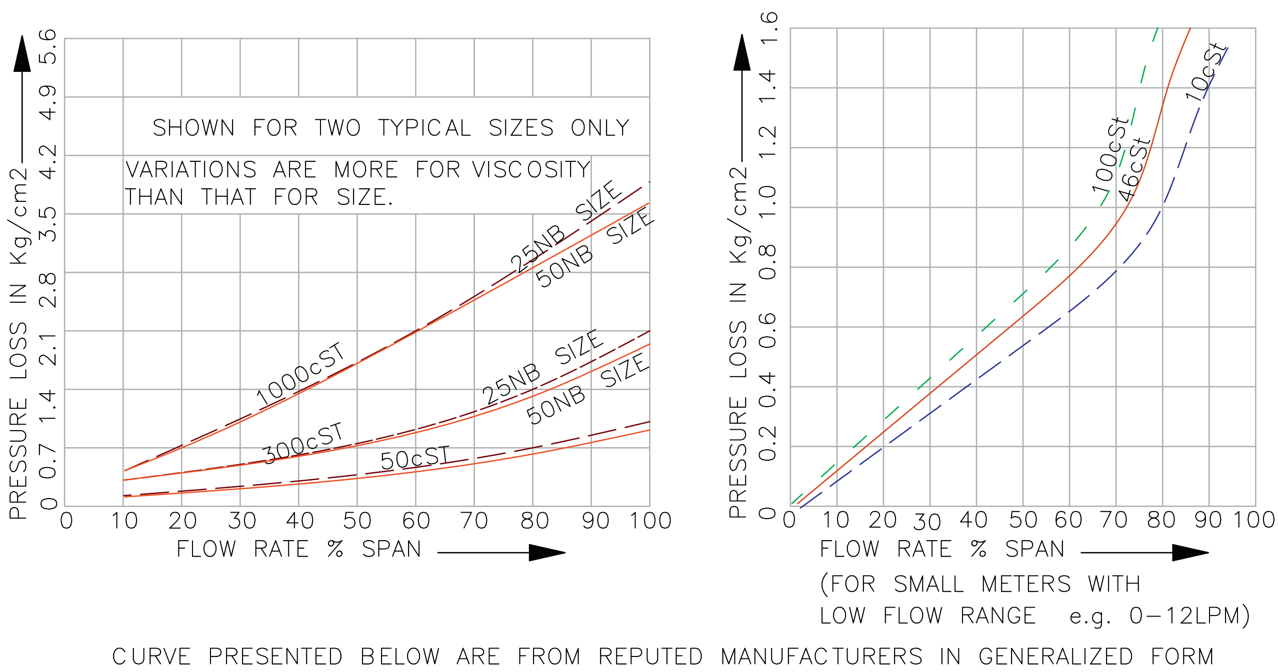

FIGURE IV/4.1.3-1 Pressure loss curves for oscillating piston meter.

do with viscosity than line size. However, in the case of smaller meters (e.g., ½″ size), the pressure drop may be less but variations with viscosity are prominent. In the latter case the range of flow may be 0.1−10 LPM. However, in order to get rid of the actual flow these are shown with respect to a 0%−100% flow range, so that there are many flow ranges. Normally meters are designed for a specific short range of viscosity and moderate variations in that viscosity will not have much of an effect. In most cases flow versus pressure loss (at different viscosity values) is given in the catalog for various sizes of meter. Therefore, in system designing it is advisable to consult the data supplied by the manufacturer.

4.2.0 Features and Applications of Oscillating Piston Meters

As stated at the initial stage of this discussion, oscillating/rotary piston flow meters are better known for their economic solutions rather than for high-precision measurement in low-flow conditions.

There are some advantages and limitations to these meters, as discussed in the following subsections.

4.2.1 ADVANTAGES OF OSCILLATING PISTON METERS

The general advantages of PD meters include no flow profile effect (hence no requirement for an inlet/outlet straight section) and no requirement for an external power supply. Some of the specific advantages of oscillating/rotary piston flow meters include, but are not limited to:

1. Simple structure and simple operation;
2. High accuracy of measurement (0.5% AR);
3. High precision at low flow rates;
4. Wide range of operation coverage;
5. Suitable for high-viscosity liquids;
6. Not greatly affected by moderate viscosity changes;
7. Possible to measure flow in both directions;
8. Compact design.

4.2.2 LIMITATIONS OF OSCILLATING PISTON METERS

Like any other PD meters it also has moving parts and is subject to wear. Other specific limitations of oscillating/rotating piston flow meters include but are not limited to:

1. The meter can handle only liquid;
2. It has a high-pressure drop;
3. The pressure drop is a function of flow rate and viscosity;
4. Normally meters are designed for a specific viscosity range;
5. Accuracy is a function of flow rate;
6. Accuracy decreases with a decrease in viscosity due to leakage;
7. Highly sensitive to suspended particles;
8. Meter may be blocked due to the presence of solids;
9. Sensitive to overload;
10. Needs monitoring and maintenance.

4.2.3 APPLICATIONS FOR OSCILLATING PISTON METERS

Oscillating/rotating piston flow meters have a wide area of application. These applications include but are not limited to the following:

1. **It is widely used for fuel flow measurements in:**
    - Trains, tractors, sailing ships;
    - Loading/unloading in fuel transportation.
2. **Measurements of:**
    - Acids;
    - Solvents;
    - Hydrogen peroxide;
    - Sodium hydroxide;
    - Distilled water.
3. Other chemical industry applications.
4. Sanitary applications.

4.3.0 General Design Details

In this section some design details are covered. The discussions are substantiated with associated data in the specification sheet provided later.

4.3.1 PHYSICAL/MECHANICAL DESIGN DETAILS

The basic design details of mechanical parts and mounting include:

1. **Accessories:** The meter supports a number of accessories normally found in PD meters such as an air eliminator, shutoff valve, filter, registers of different kinds, such as electronic, mechanical, remote, totalizer, batch controller.
2. **Mounting:** Normally these are suitable for horizontal and angular mounting.
3. **Constructions materials:** The wetted parts have 316 SS and ETFE so that it can cover a wide range of liquids.
4. **Process pressure withstand capability:** Meters of different models are available to support process pressure from low pressure to high pressure of up to 40 bars or higher.
5. **Process temperature:** Various models of meters are available to withstand process temperatures from −2°C to 80°C. Therefore, the meters can cover wide application ranges.

4.3.2 ELECTRICAL DESIGN DETAILS

Although this is a mechanical meter, all are normally available with electrical display and transmission facilities. They are discussed in this subsection.

1. **Pick up and drive:** the number of rotations of the piston equates to the volume flow. Therefore, when simple mechanical design is considered, the rotation is transmitted to the gear train and this is registered directly. On the other hand, when an electronic display or transmission is considered, the same is done with the help of a magnetic drive (diaphragm). Hall effect pick ups are also used.
2. **Register:** There is a wide variety of possible registers these include:
   - Mechanical on flow meter;
   - Electronic on flow meter;
   - Electronic for remote transmission;
   - Batch control application.
3. **Output types:** There are a number of output functions carried out by the meter and these include (as indicated earlier):
   - Batch controlling;
   - Remote totalizing;
   - Local totalizing and rate display.
4. **Other electrical functions:** In addition to the above remote transmission, recording, data logging, and pump control functions can also be done.
5. **Electrical enclosure:** Available in NEMA 4X/IP65 may IP 67.
6. **Load to drive:** 500 Ω for 4−20 mADC.

4.3.3 ENVIRONMENTAL CONDITIONS

Normally meters can be used in wide ambient temperature range from −10°C up to 60°C with humidity up to 90%.

4.4.0 Meter Size, Selection, and Performance

As mentioned earlier these meters are available with high precision, especially in low-flow range when compared with meters of the same capacity in other categories. Short discussions are now presented in terms of the various sizes of meters with flow range and viscosity parameters so that the reader can select a suitable meter.

4.4.1 METER SIZES FOR SELECTION

Various meter sizes with associated flow ranges are presented in Table IV/4.4.1-1. One should note that these are taken from various reputed manufacturers and presented in the generally available form. Actual data may vary from those in the table.

TABLE IV/4.4.1-1 Oscillating Piston Meter Size and Flow Range

Size(NB)	Flow Range	Accuracy/Error	High (+) Error	High (−) Error	Remarks
15	3.8–38	−0.4 to −1.2% AR	0.4% @ 10%	1.2% @ 100%	Visco: 1 cSt
		−0.2% to +0.4 AR		0.2% @ 100%	Visco: 10 cSt
25	26.6–266	−0.4 to +0.5% AR	0.5% @ 21%	0.4% @ 100%	
50	57–570	−0.4 to +0.5% AR	0.5% @ 16%	0.4% @ 100%	
80	114–1140	−0.5 to +0.4% AR	0.5% @ 20%	0.5% @ 100%	

Flow ranges are in LPM; all accuracies are in AR and errors are mentioned (@% flow range). Visco: viscosity.

4.4.2 OVERALL PERFORMANCE

Variations in flow meter performances are listed here:

1. **Overall accuracy:** Normal 1.0% AR; high precision: 0.5% AR;
2. **Repeatability:** 0.1%;
3. Typical turndown 10:1 as shown in the table above.

Values given here are generalized values that may vary with actual flow meter data.

4.5.0 Specification of Oscillating/Rotating Piston PD Meters

In this section a brief specification of a rotating piston meter is presented as Table IV/4.5.0-1. The generalized data presented here are from reputed manufacturers, so may differ from one particular manufacturer to another. Also, it is to be noted that all these parameters are mainly the *highest* parameters available and *not all are applicable for each meter*.

TABLE IV/4.5.0-1 Specification of Oscillating/Rotating Piston Meter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Liquid in the application in medium viscosity range with lubricating property		
2	Design pressure	Max 40 bar		
3	Design temp.	80°C (temperature)		
4	Viscosity	20 to 10^3 cP available		
5	Registration	In US/Imperial gallons/L/m^3		Options available
6	Pick up type	Magnetic/Hall/switch		
7	Output	Pulse, 4–20 mADC, with photoelectric and/or other converter		
8	Output function	Local rate, totalized display, remote transmission, batch control/register, communication		

Continued

TABLE IV/4.5.0-1 **Specification of Oscillating/Rotating Piston Meter—cont'd**

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
Materials of Construction (MOC)				
9	Casing/housing	316 SS/brass/aluminum		
10	Measuring chamber	316 SS/brass/aluminum		
11	Piston	ETFE/316SS/FKM*		Refer Fig. IV/4.2.0-1
12	Flange	Stainless steel		
13	Drive assembly	Stainless steel		
14	Shaft	316 SS (drive assembly)		*Fig. IV/3.5.0-1
15	Packing gasket	Teflon, silicon, rubber		
16	Seal	Teflon, silicon, rubber		
17	Register	ABS plastic, aluminum, bronze		
Process Connections & Mounting				
18	Process	Mainly flanges of different sizes from DN 25 to DN 80. For smaller sizes screwed connection, e.g., ½″ to 2″ NPT		
19	Electrical	M20, ½″ NPT/BSP female or DIN 43650 plug		
20	Mounting	Horizontal, angular		
Performance and Other Details				
21	Accuracy	±1.0% to 0. 5% AR*		*Variation with viscosity range
22	Repeatability	0.1% AR		
23	Certification	Certification for safety applications		
24	Application	Subsection 4.2.3		
25	Accessories	Refer to Subsection 4.3.1.1		
26	Special feature	To specify		

In organic chemistry ETFE stands to represent *Ethylene tetrafluooethylene* which is a plastic material with fluorine to offer very high corrosion resistance and strength. It is usable over wide Temperature range. It can withstand wide range of fluids- hence popular in instrumentation. It can withstand temperature: little over 90°C (short term) & little over 60°C (long term).

FIGURE IV/4.2.0-1 ETFE material.

4.6.0 Installation Details

Installation of the meter is similar to the installation of other PD meters already discussed. A few pertinent points for oscillating piston disks are enumerated below:

4.6.1 PREINSTALLATION ISSUE

The most important issue is to go through the installation guidelines provided by the manufacturer so that the installation is correct. *Not only here, but in all cases it is important to follow the manufacturer's guideline because the manufacturer probably has the best knowledge about the requirements for the product. Also, the product's guarantee is protected as long as the guidelines are followed.* Some common and major issues applicable not only for this flow meter but for all flow meters are as follows:

1. Unpack the materials following the safety guidelines provided by the manufacturer. Also remove all unnecessary materials such as the transportation retainer etc.
2. Inspect the pipeline to ensure it is clean and free from welding beads, etc.
3. Make sure that the operating parameters such as process pressure, temperature, and flow range are well within the limit of the meter.
4. Orient the flow meter in the direction marked in the meter (as applicable).

4.6.2 ACCESSORIES INSTALLATION ISSUES

As is common with any PD meter a number of accessories may be necessary. These issues have been discussed already in connection with another flow meter, i.e., the nutating disc/oval meter. The requirements stated there also apply here. The requirements for major accessories for PD meters (applicable for others also) are as follows:

1. **Air eliminator:** It is not always necessary to install an air eliminator for the meter but when it is used it should be as close as possible to the inlet of the meter so that maximum elimination is feasible [15].
2. **Strainer:** A strainer of size 40 mesh when used should be put directly at the meter inlet. If this is not possible then any associated piping must be clean.
3. **Shutoff valve:** Normally the shutoff valve is installed downstream to control the flow. Also, for continuation of operation, inlet and outlet shutoff valves are necessary for isolation and in that case a bypass valve is essential to continue the operation as shown in Figs. IV/2.4.0-2 and IV/3.6.0-1. Subsections 2.4.2 and 3.6.2.8 may be referred to.

4.6.3 INSTALLATION ISSUES

Basic issues related to meter installation have been discussed at length earlier, therefore they are not repeated here. Other allied points include:

1. **Mechanical connections:** The mechanical connection should be free from any stress or stain. Some recommend mechanically fastening the connection pipes approximately 50 mm from the connection thread [14]. All the mechanical connection threads should be sealed properly. For flange connections proper tightening of bolts and gasket positions are important and care should be taken with these.
2. **Electrical issues:** The power supply should be checked for proper connections as necessary. All connections are made as per assigned pin correctly.
3. Grounding is an important issue and should be properly addressed.
4. For intrinsic connections extra care should be taken. For further details Ref. [10] may be referred to.

With this discussion on oscillating/rotating pistons concluding, discussions now move to rotating vane meters.

5.0.0 ROTATING VANE METERS

Rotating vane PD flow meters are extensively used for custody transfer, especially in oil and petroleum industries. Like other PD meters this

flow meter is also well suited for clean liquid with lubricating property and medium viscosity.

5.1.0 Rotating Vane Flow Meter Description

With reference to Fig. I/3.1.2-4, the discussions start with a recap of the operating principles of rotating vane PD meters.

5.1.1 PRINCIPLES OF OPERATION

Basically, in comparison to the rotary piston flow meter, this meter rotor rotates about the fixed axis of the shaft. There are two versions of this meter, as shown in Fig. I/3.1.2-4. One version has a static cam which acts as a guide for the vanes in Fig. I/3.1.2-4(A—D). The other version does not have a cam and the rotor is an eccentric rotor with spring-loaded vanes as depicted in the right-hand side illustration in Fig. I/3.1.2-4.

1. **Meter with a cam:** In the cam version, the vanes/impellers divide the entire space into two/four equally divided compartments as shown in Fig. I/3.1.2-4. When fluid appears at the inlet, on account of differential pressure, the liquid pushes vane 1 to change position. A fixed quantity of fluid in the measuring chamber is then pushed out and goes part of the way to the outlet. Vane 2 is then rotated. As the vanes follow the profile of the static cam one set of impellers/vanes is in continuous contact with the casing to deliver a fixed volume of liquid from the inlet to the meter's outlet. From the figure it can be seen that in the first position (A) the impeller set comprising 1 and 4 is touching the casing to ascertain the volume and in positions B, C, and D the impeller sets are 1—3, 1—2, and 2—4, respectively—explained for clarity of understanding. Hence this is to be read in conjunction with Fig. I/3.1.2-4 (left part).
2. **Without a cam:** A spring-loaded vane is attached to the rotor described above. In this version the rotor is eccentric with respect to the measuring chamber. The spring-loaded vanes/impellers seal liquid between the eccentrically mounted rotor and the casing and finally transport the liquid to the outlet port.

In both cases, the rotation of the shaft is transmitted upward through a set of gear trains. Normally a Hall sensor/magnetic sensor or mechanical are used the rotary motion of the vane, i.e., the rotation of the shaft for totalizing, the flow.

5.1.2 DESCRIPTIVE DETAILS OF ROTATING VANE PD METERS

In a rotating vane PD meter the vanes are extended or retracted on account of the rotation of the vanes around the shaft *following a static cam profile* or due to rotation of an eccentric rotor to which the spring-loaded vanes are attached as shown in Fig. IV/5.1.2-1. As stated earlier, on account of the extension and retraction of the vanes defined volume sections are created. These are highlighted in Fig. IV/5.1.2-1.

The major components of rotating vane meters in both versions include:

- Housing;
- Cover plate;
- Inlet filter (as applicable);
- Measuring chamber;
- Blades/vanes with roller;
- Rotor assembly with static cam;
- Wetted fastener;
- Spring-loaded vanes (W/O cam);
- Vane slot (W/O cam);
- Eccentric rotor (W/O cam);
- Gasket;
- Flow conditioning base;
- Shaft;
- Gear trains;
- Magnetic/Hall effect pick up;
- Magnet support assembly;
- *Process connection:* flange;
- Calibrating unit (mech.);
- Top display unit with adapter and electrical connector;
- Display unit rate/total;
- Pulse converter/transmitter, etc.

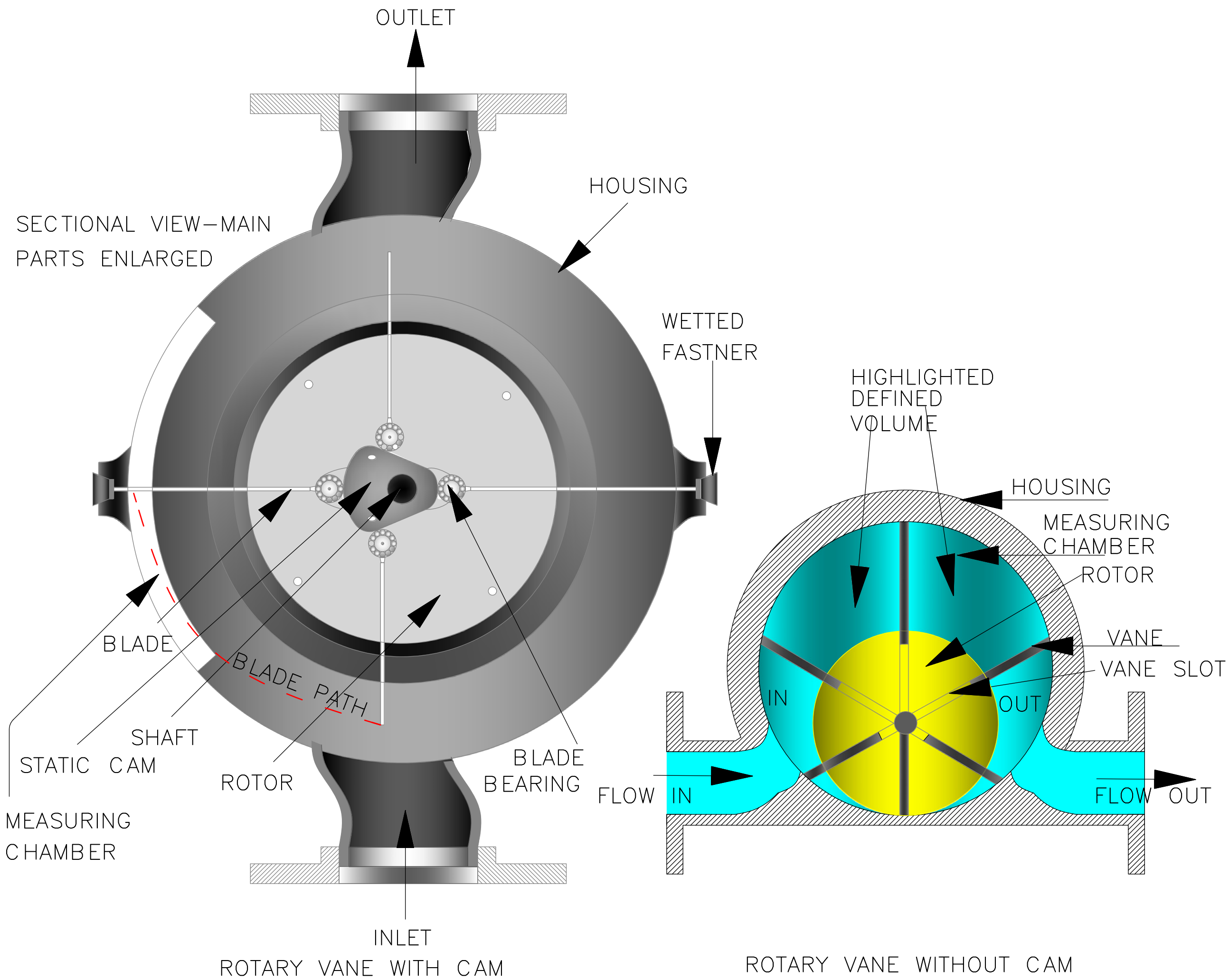

FIGURE IV/5.1.2-1 Rotating vane meter GA. *Based on an idea from Smith Meter (FMC).*

When the calibration unit and transmitter, etc. are removed one would find, at the bottom, that the blades divide the measuring chamber into a definite volume section, with the inlet and outlet sections isolated. The rotor block rotates around the shaft and the blades are extended and retracted on account of the static cam in the cam version, or on account of the spring action, with the blades extended and retracted in the vane slot in the eccentric rotor in the other version. In both cases the rotation of the rotor is transmitted with the help of gear trains. The inlet and outlet openings are located on the chamber wall at both sides of the measuring chamber. As stated earlier, this type of meter is widely used in the oil and petroleum industry for varied purposes. Like any other PD meters they are used for clean liquids with varying viscosity ranges. The meters are available in various sizes to measure in the ranges from a few liters per minute of low-viscosity liquid to as high as ∼ 1.2 m^3/min of viscous particle-laden crude oils [7], with viscosity ranging from 0.7 cSt to 20 cSt being commonly available. The maximum process pressure and temperature withstand capability are around 70 bar and 180°C (min −10°C), respectively.

Normally these meters have flange connections but screwed connections are also possible. Stainless steel is the most common construction material. Since these are often used for custody transfers high accuracy of up to 0.05% AR is also available.

5.1.3 PRESSURE LOSS IN THE METER

Like other PD meters, in rotating vane flow meters pressure loss is a function of flow. However, the pressure loss is not greatly affected by viscosity. Normally these meters are available in various sizes and hence various flow ranges. Each of these flow ranges or meter sizes has a different pressure loss. These meters are also suitable for a band of viscosity ranges, in which four or five such viscosity bands cover a total viscosity ranging from 0.7 to 20 cSt. These viscosity bands also have variable accuracy. In Fig. IV/5.1.3-1 variations in pressure losses with flow ranges for different size meters have been shown. These data are taken from one reputed manufacturer.

From the figure it is observed that the higher the flow rate/meter size, the steeper will be the pressure loss curve. However, in order to get rid of the actual flow these are shown with respect to a 0%–100% flow range so that many flow ranges fit. Normally meters are designed for a specific short range of viscosity and moderate variations in that viscosity will not have much of an effect. In most cases flow versus pressure loss (at different viscosity values) is given in the catalog for various sizes of meter. Therefore, for a system design it is advisable to consult the data supplied by the manufacturer.

5.2.0 Features and Applications of Rotating Vane PD Meters

As stated at the initial stage of the discussion, rotating PD meters are extensively used for custody transfer applications on account of their

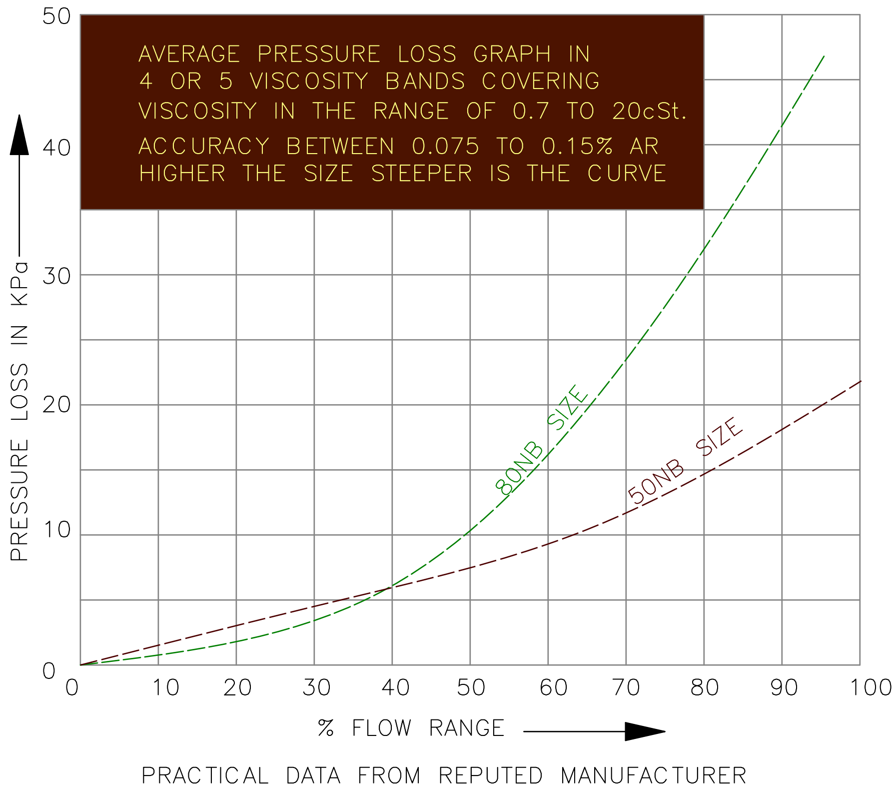

FIGURE IV/5.1.3-1 Pressure loss in RV PD meter.

precise measurement. Various advantages and limitations of these meters are discussed in the following subsections.

5.2.1 ADVANTAGES OF ROTATING VANE PD METERS

The general advantages of PD meters include that they have no flow profile effect (hence no requirements for an inlet/outlet straight section) and no requirement for an external power supply. Some of the specific advantages of oscillating/rotary piston flow meters include but are not limited to:

- Compact, fully sealed, and reliable design;
- Precise measurement of wide flow range;
- Not affected much by moderate viscosity variations;
- Built-in temperature sensor for compensation;
- Wide selection of materials—hence useable for a wide range of applications;
- Longer service life;
- Precise high-rated performance;
- Built-in temperature compensation;
- Integral electronics.

5.2.2 DISADVANTAGES OF ROTATING VANE PD METERS

Like any other PD meters, these meters also have moving parts and are subject to wear. Some other specific limitations of oscillating/rotating piston flow meters include but are not limited to:

- Suitable for clean fluid so integral filter may be necessary;
- Limitation comes from seal leakage;
- Pressure loss increases with flow range;
- High wear and tear.

5.2.3 APPLICATIONS OF ROTARY VANE PD FLOW METERS

These meters have a wide application area. These include but are not limited to the following applications:

- Custody transfer in oil and petroleum industry;
- Heavy goods industries;
- Automobile workshops;
- Cooling water monitoring;
- Waste water monitoring;
- Food processing plants;
- Various chemical plants;
- Biofuel blending and other refined products;
- Mobile service vehicles;
- Measurement of crude oils containing paraffin wax.

5.3.0 General Design Details

In this section some design details are covered. The discussions will be substantiated with associated data in the specification sheet provided later.

5.3.1 PHYSICAL/MECHANICAL DESIGN DETAILS

The basic design details of mechanical parts and mountings have been listed below. One needs to note that the data indicated below are the highest possible data available in different models:

- *Accessories:* The meter supports a number of accessories normally found in PD meters such as an air eliminator, shutoff valve, filter, registers of different kinds, such as electronic, mechanical remote, totalizer, batch controller. Many of the meters have an inlet filter built in. In some cases a built-in temperature probe for temperature compensation is also available.
- *Mounting:* Normally these are suitable for horizontal mounting.
- *Construction materials:* A wide range of materials are used; the main materials used include 316 SS, brass/PTFE housing with a ceramic/sapphire axel.
- *Process pressure withstand capability:* Different models are available to support process pressures from low pressure to pressure as high as 70 bars.
- *Process temperature:* Various models are available to withstand process temperatures from −29°C to 180°C. Therefore, these meters can cover a wide range of applications.

- *Long service life:* To achieve a longer service life many use a ceramic hybrid roller, and PEEK (Refer Fig. IV/3.5.0-1) wear strips on the blade tip [16].
- Many designs are available where there is a significant reduction in mechanical parts in comparison to conventional meters, giving a better design.

5.3.2 ELECTRICAL DESIGN DETAILS

Although this is a mechanical meter, all of them are normally available with electrical display and transmission facilities; these are discussed in this subsection.

Pick up and drive: As explained above, the rotation of the shaft is transmitted to the gear train which registers this directly. On the other hand, when an electronic display or transmission is considered, this is done with the help of a magnetic drive (diaphragm). Hall effect pick ups, as discussed earlier.

Register: There is a wide variety of registers available, including:

- Mechanical on-flow meter;
- Electronic on-flow meter;
- Electronic for remote transmission;
- Batch control application.

Output types: The outputs are normally pulse output with voltage dependent on the power supply used. There can be a Reed switch pulse output or Hall effect sensor pulse output. When transmitters/converters are used it is possible to get 4−20 mADC output. There are a number of output functions carried out by the meter and these include (as indicated earlier):

- Batch controlling;
- Remote totalizing;
- Local totalizing and rate display.

Electrical enclosure: This is available in NEMA 4X/IP65 enclosure. Also enclosures are available with IP 67.

Load to drive: 500 Ω for 4−20 mADC; however, a normal load for pulse output is around 300 Ω with a lower peak voltage. However, this depends on the power supply used.

5.3.3 ENVIRONMENTAL CONDITION

Normally meters can be used in a wide ambient temperature ranging from −10°C up to 60°C, with humidity up to 90%.

5.4.0 Meter Size, Selection, and Performance

Short discussions are presented here in terms of the various sizes of meters with flow range connection sizes and pressure loss parameters.

5.4.1 METER SIZES FOR SELECTION

Various meter sizes with associated flow ranges are presented in Table IV/5.4.1-1. One should

TABLE IV/5.4.1-1 Rotating Vane PD Meter Size and Flow Range

Size(NB) mm	Flow Range (LPM)	Accuracy	Connection	Pressure Loss in Bar
6	0.1−0.5/0.5−7	±2.5% FSD	G ¼″/¼″ NPT	1.0
15	0.2−2.0/1-16	±2.5% FSD	G ½″/½″ NPT	0.7
40	2−36	±2.5% FSD	G ¾″/¾″ NPT	0.9
50	38−570	0.1	ASME 150 FL	0.25
	11−570	0.2		
80	127−1900	0.1	ASME 150 FL	0.45
	38−1900	0.2		

All the values given are typical as collected from reputed manufacturers and generalized, so they may vary slightly with actual data.

note that these are taken from various reputed manufacturers and are presented in the generally available form. The actual data may vary from those in the table.

5.4.2 OVERALL PERFORMANCE

Variations of performances of the flow meter are listed below:

- *Overall accuracy:* Normal 0.15 % AR high precision: 0.05% AR possible;
- *Repeatability:* 0.02%−0.01% possible;
- Typical turn down 50:1 possible; refer to the Smith meter.

Values given here are generalized values that may vary with actual flow meter data.

5.5.0 Specification of Rotating Vane PD Meters

In this section, a brief specification of a rotating vane meter is presented as Table IV/5.5.0-1. The generalized data presented here are from reputed manufacturers, so they may differ from one particular manufacturer to another. Also, it is to be noted that all these parameters are the main *highest* parameter available and *not all are applicable for each meter*.

TABLE IV/5.5.0-1 Specification of a Rotating Vane Meter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Liquid in the application in medium viscosity range		
2	Design pressure	Max 40 bar		
3	Design temp.	80°C (temperature)		
4	Viscosity	0.7 to 20 cSt (standard) in different bands		
5	Registration	In US/imperial gallons/L/m^3		Options available
6	Pick up type	Magnetic/Hall/reed switch		
7	Output	Pulse, 4−20 mADC, alarm output and with photoelectric and/or other converter		
8	Output function	Local rate, totalized display, remote transmission, batch control/register, communication		
Materials of Constructions (MOC)				
9	Casing/housing	SS/CS/brass/brass-plated nickel		CS: carbon steel SS: stainless steel
10	Measuring chamber	SS/CS/CI/brass		CI: cast iron
11	Rotor	CI/polypropylene oxide		
12	Vane	Polypropylene/hard anodized aluminum with PEEK* stripes		*PEEK: polyetheretherketone (refer Fig. IV/3.5.0-1)
13	Flange	Stainless steel		

Continued

TABLE IV/5.5.0-1 Specification of a Rotating Vane Meter—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
14	Shaft	Hardened stainless steel		
15	Packing gasket	Teflon, silicon, rubber		
16	cam	Hardened stainless steel		
17	FC* base plate	Polypropylene oxide		*FC: Flow conditioning
18	Seal	Teflon, silicon, rubber		
19	Register	ABS plastic, PTFE, bronze		
Process Connections and Mounting				
20	Process	Both flange and screwed connections Flange: ASME 150 lb/screw: G ¼ or ½″ or NPT ¼″ or ½″		
21	Electrical	M20, ½″ NPT/BSP female or DIN plug		
22	Mounting	Horizontal		
Performance and Other Details				
23	Accuracy	±0.2% to 0. 1% AR* (0.05% also availble)		
24	Repeatability	0.02% to 0.01% AR		
25	Certification	Certification for safety applications		
26	Application	Subsection 5.2.3		
27	Accessories	Similar to rotating piston and as described in Subsection 5.3.1		
28	Special feature	To specify		

5.6.0 Installation Details

Installation of the meter is similar to the installation of other PD meters already discussed. A few pertinent points for oscillating vanes are enumerated below:

1. **Preinstallation issue:** Similar to that discussed in Subsection 4.6.1.
2. **Accessories and installation issue:** As is common with any PD meter a number of accessories may be necessary. These issues have been discussed already in connection with other flow meter, i.e., nutating disc/oval meters. The requirements stated there may be followed here. The requirements stated in Subsection 4.6.2 may be followed here also.
3. **Other installation issues:** Subsection 4.6.3 may be followed here also.

With this discussions on rotating instruments concluded, we now look discuss reciprocating type meters.

6.0.0 RECIPROCATING PISTON PD METERS

Reciprocating piston PD meters are some of the oldest meters. Like other PD meters this flow meter is also well suited for clean liquids with medium viscosity.

6.1.0 Reciprocating Piston PD Meter Description

In Fig. I/3.1.2-5 a short description of a reciprocating piston flow meter which uses a sliding valve is given. Further details are given here.

6.1.1 PRINCIPLES OF OPERATION

Although the basic principles of operation in both cases are similar, there are a few variations from a working process point of view, as discussed here.

1. **Piston meter with a slide valve:** This meter consists of three/four plungers, each of them fitted with a cylinder acting as a measuring chamber. The plungers are joined to a wobble plate, with a shaft extending from its upper surface for the sensing side. The wobble plate with a valve pivot is used to drive a sliding valve to cause the cylinder to open in sequence and controls the sequence of events. The wobble plate shaft is kept at an inclined position to allow the plate to tilt from side to side, preventing the same from rotation by four guide pins on the pivot bracket assembly. From the inlet, fluid flows into the meter chamber located in the upper meter housing. As the sliding valve travels around the meter chamber, it sequentially opens and closes the inlet and outlet of each measuring chamber. The sliding valve starts in position with one measuring cylinder open to the downstream flow. The plunger for the corresponding cylinder is in the upper position with the cylinder below open to the outlet as shown in the left-hand side diagram in Fig. IV/6.1.2-1. With the upper housing filled with fluid at line pressure, the differential pressure between the inlet and outlet sides forces the plunger to the bottom of the cylinder. As the plunger is pushed toward the bottom, fluid is expelled from the measuring cylinder to the central opening connected to the outlet. When this takes place, another plunger is forced from the down position to the upper position, as the inlet fluid gushes through the left-side opening. As this happens, the sliding valve changes position and moves to open the inlet of this cylinder. As the plunger moves upward, it draws fluid into the bottom of the measuring cylinder through the open port in the meter chamber. Once this plunger reaches the upper position, the cycle will repeat, so long as fluid continues to enter the meter, i.e., there is fluid flow. *When fluid flow stops, the pressure in the meter equalizes and motion stops. Therefore, the meter only operates when fluid is flowing.* In this connection Fig. I/3.1.2-5 in chapter I may be referenced for sliding valve operation and another way of functioning of the meter.
2. **Reciprocating piston meter with four plungers:** As stated earlier there are several versions of these meters. In this version, as shown in the cross-sectional top view (right-hand side diagram) of Fig. IV/6.1.2-1 there are four sets of plungers fitted in a cylindrical measuring chamber (as discussed above) arranged around the central crank shaft. Each one of these plungers drives the adjacent plunger. Also, each of these measuring chambers is connected to an exhaust port. All of these exhaust ports are internally connected to the outlet side of the meter. The fluid enters the meter at the base below the plunger sets, and two ports in the cylinder draw the fluid [17] in along with other parts. From the base fluid comes to the meter through the central part and is distributed to one plunger after another set in sequence. As the meter shaft rotates the fluid from one of the pistons it goes to drive an adjacent plunger. As that piston reaches the end position, the fluid in the former plunger set (sending fluid for other plunger drive) becomes connected to its exhaust port

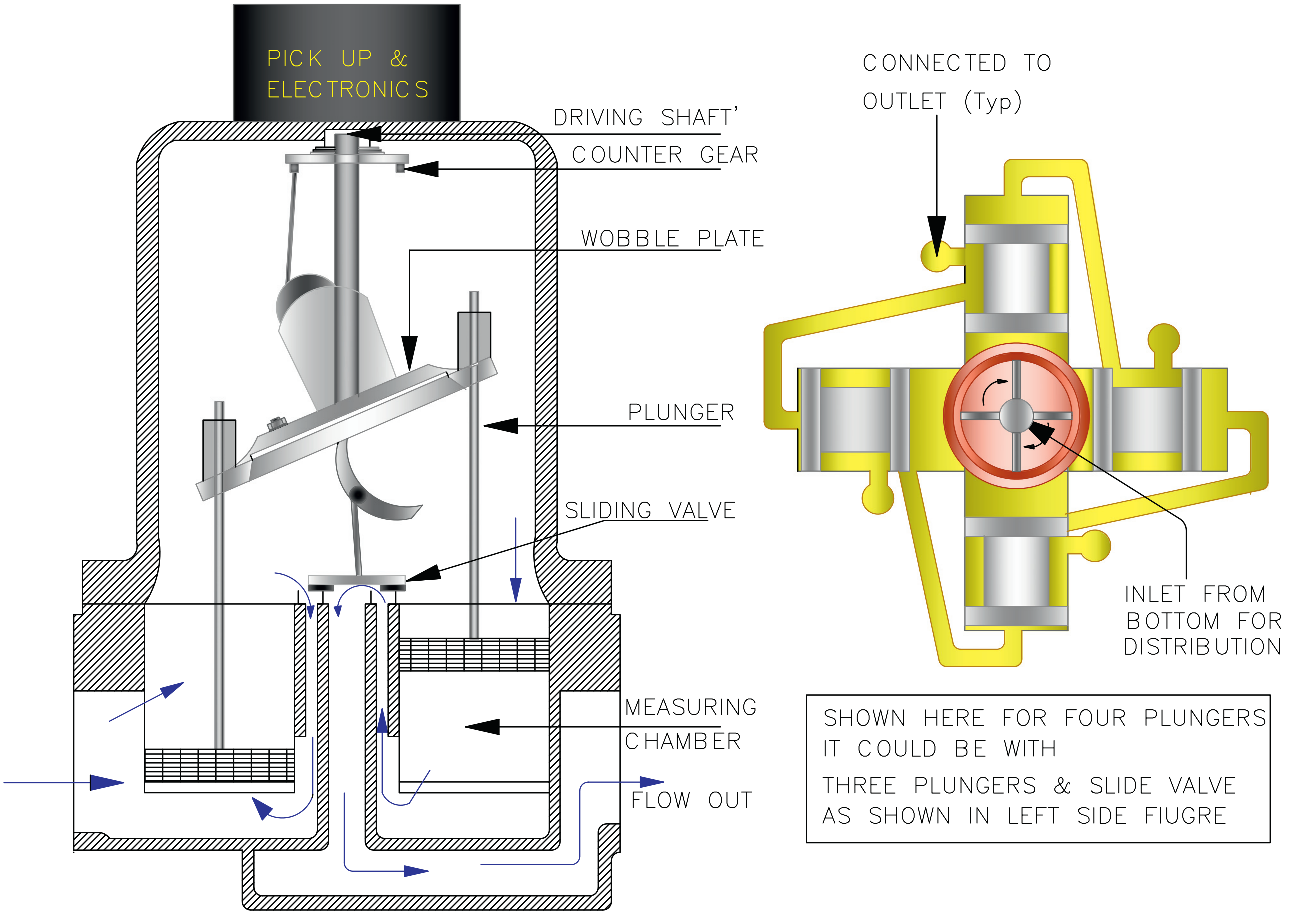

FIGURE IV/6.1.2-1 Reciprocating piston PD meter.

which is connected to the meter outlet. Then, on account of rotation, the next set comes into action. Thus, in this way all the plungers operate sequentially, and liquid from the base, passing through one of the plungers and the measuring chamber goes to the outlet. Each time a measured quantity of fluid enters and is expelled. The rotational motion of the upper plate is transmitted and sensed at the upper electronic part. Therefore, by counting the rotations, the flow of fluid can be measured/computed. Therefore liquid entered from the bottom performs two functions viz. pushing part through exhaust port to outlet and part to drive the adjacent cylinder to become active for next sequence.

6.1.2 DESCRIPTIVE DETAILS OF ROTATING VANE PD METERS

The major components of both versions of reciprocating piston PD meters mainly consist of:

- Housing;
- Cover plate;
- Inlet filter (as applicable);
- Cylindrical measuring chambers;
- Set of plungers;
- Slide valve sets (when applicable);
- Wobble plate;
- Center gear;
- Eccentric rotating plate;
- Gasket;
- Flow conditioning base;

- Shaft;
- Gear trains;
- Magnetic/Hall effect pick up;
- Magnet support assembly;
- *Process connection:* flange/screwed;
- Calibrating unit (mechanical unit);
- Top display unit with adapter and electrical connector;
- Display unit rate/total;
- Pulse converter/transmitter, etc.

In the case of a meter with a sliding valve, as stated earlier there will be one wobble plate which has a shaft (as shown) extending from its upper surface and a valve pivot attached beneath it [18]. The valve pivot drives the sliding valve. The wobble plate is always at an inclined position by the center gear to preventing it from rotating. In the other version, as stated earlier, there are two fluid ports on the cylinder wall, a port at the cylinder top, and a grooved piston which enable the fluid to enter at the meter's central cavity [17] from where fluid passing through the piston chamber combination is measured and expelled from the meter in sequence. There is a wide range of meters available in different sizes to accommodate very low flow of 0.2 L/min to 189 L/min from different manufacturers. While some manufacturers' models withstand moderate pressure, others can offer models to withstand process pressure up to 200 bar (e.g., P213 of Max) and even up to 500 bar (max machinery models with PxxxHS). Similarly, the meters support wide temperature ranges of ~ -30 to 225°C in different models from different manufacturers. Meters are used with the recommended filter with different mesh sizes. Meters are available with an accuracy of 0.1% AR.

6.1.3 PRESSURE LOSS IN THE METER

As in other PD meters, in the reciprocating piston PD meter pressure loss is a function of flow as well as viscosity. In cases of low flow the viscosity effect is predominant. All manufacturers provide a pressure loss curve against flow at different viscosity conditions and/or the range of viscosity within which the meter can operate. Such curves are similar to what has been discussed and described in connection with other meters and hence is not repeated here. As the meters cover various sizes from 1/8″ up to 3″, covering a wide range of flow and viscosity ranges from, e.g., 3 cP to 10,000 cP, there are a large numbers of curves to cover (in log scale). The designer needs to consult these manufacturer-supplied curves.

6.2.0 Features and Applications of Reciprocating Piston PD Meters

Reciprocating piston meters find a wide range of applications, some with special features. The various advantages and limitations of these meter are discussed in the following subsections.

6.2.1 ADVANTAGES OF RECIPROCATING PISTON PD METERS

The general advantages of PD meters include no flow profile effect (hence no requirements for an inlet/outlet straight section) and no requirement for an external power supply. Some of the specific advantages of oscillating/rotary piston flow meters include but are not limited to:

- High accuracy and repeatability;
- Wide turndown ratio of 200:1;
- Very good choice for batch applications and slow flow measurement;
- Wide range of flow;
- Broad range of viscosity and changes in viscosity;
- Wide range of pressure- and temperature-withstanding capability;
- Compatibility for a wide range of fluids;
- Proven design and reputation;
- Compact, fully sealed, and reliable design;
- Integral electronics.

6.2.2 DISADVANTAGES OF RECIPROCATING PISTON PD METERS

Like any other PD meters these also have moving parts and are subject to wear. Some other specific limitations of oscillating/rotating piston flow meters include but are not limited to:

- Suitable for clean fluid so inlet filtration may be necessary;
- Limitation comes from seal leakage;
- Weight and cost increase with size;

- Pressure loss increases with flow range;
- High wear and tear.

6.2.3 APPLICATIONS OF RECIPROCATING PISTON PD FLOW METERS

These meters have widespread applications. These specific application areas include but are not limited to the following:

- Batch control process;
- Fuel measurement systems such as for gasoline and diesel;
- Chemical injection systems;
- Stationary/mobile fuel-measuring system;
- Fuel consumption in aircraft/vehicles;
- Diesel exhaust measurement system;
- Biofuel blending and consumption measurements;
- Testing of hydro-servo valves;
- Odorant injection and oiler flow measurements;
- Dispensing machines.

6.3.0 General Design Details

In this section some design details are covered. The discussions are substantiated with associated data in the specification sheet provided later.

6.3.1 PHYSICAL/MECHANICAL DESIGN DETAILS

The basic design details of mechanical parts and the mounting are listed below. It should be noted that the data indicated below are the best possible data available in different models:

- *Accessories:* Similar to Subsection 4.3.1.1.
- *Mounting:* Normally these are suitable for horizontal mounting but in some cases vertical mounting is also allowed.
- *Construction materials:* A wide range of materials are used; the most commonly used materials include SS 303/316/440C, ductile iron, Teflon, Viton, etc. for different parts in different models.
- *Process pressure withstand capability:* Meters of different models are available to support process pressures from low pressure to as high as up to 200 bars.
- *Process temperature:* Various models are available to withstand process temperatures from −29 to 225°C. Therefore, these meters can cover a wide range of applications.

6.3.2 ELECTRICAL DESIGN DETAILS

Although this is a mechanical meter, they are normally available with electrical display and transmission facilities, and so they are discussed in this subsection.

Pick up and drive: As explained above, the rotation of the shaft is transmitted to the gear train and is registered directly. On the other hand, when an electronic display or transmission is considered, this is done with the help of magnetic/Hall effect pick ups, as discussed earlier.

Other electrical properties are similar to what has been described for rotating vane type meters.

6.3.3 ENVIRONMENTAL CONDITION

Normally meters can be used in a wide ambient temperature range, from −40°C up to 80°C, with humidity up to 90%.

6.4.0 Meter Performance

Variations of flow meter performances are listed here:

- *Overall accuracy:* Wide ranges of accuracy from 1.0% to 0.1% AR possible;
- *Repeatability:* 0.02%−0.01% possible;
- Typical turndown 200:1 possible, refer to the Smith meter.

Values given here are generalized values that may vary with actual flow meter data.

6.5.0 Specification of Reciprocating Piston PD Meters

In this section a brief specification of the reciprocating piston PD meter has been presented as Table IV/6.5.0-1. The generalized data presented here are from reputed manufacturers, so they may differ from one particular manufacturer to another. Also, it should be noted that all these parameters are the main *highest* parameter available and *not all are applicable for each meter.*

TABLE IV/6.5.0-1 Specification of Reciprocating Piston PD Meter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Liquid in the application in wide viscosity range		
2	Design Pressure	Max 200 (or even 500) bar		
3	Design Temp.	−10 to 225°C		
4	Viscosity	1 to 10,000 cP in different bands		
5	Registration	In US/Imperial gallons/L/m^3		Options available
6	Pick up type	Magnetic/Hall/switch		
7	Output	Pulse, 4—20 mADC, alarm output and with photoelectric and/or other converter		
8	Output function	Local rate, totalized display, remote transmission, batch control/register, communication		
Materials of Constructions (MOC)				
9	Casing/housing	SS303, SS316, anodized aluminum		
10	Measuring chamber	SS316/CI/nI hardened stainless steel		CI: cast iron
11	Plunger	SS316/CI/nI hardened stainless steel		
12	Ball bearing	SS 404C SS, SS ceramic		
13	Flange	Stainless steel		
14	Shaft	Hardened stainless steel		
15	O ring	Teflon, viton, FKM[a]		
16	Packing/seal	Viton, FKM, Teflon, Simriz[b]		
17	Register	ABS plastic, PTFE, bronze		
Process Connections and Mounting				
18	Process	Both flange and screwed connection flange: ASME 150 lb/Screw: NPT ¼″ or ½″		
19	Electrical	M20, ½″ NPT/BSP female or DIN plug		
20	Mounting	Horizontal and vertical mounting is possible		
Performance and Other Details				
21	Accuracy	±0.2% to 0. 1% AR* (typical highest data)		
22	Repeatability	0.02% to 0.01% AR		
23	Certification	Certification for safety applications		
24	Application	Subsection 6.2.3		
25	Accessories	Similar to rotating piston as described in Subsection 4.3.1.1		
26	Special feature	To specify		

[a]****FKM**: *fluoroelastomer (ASTM) similar to viton.*
[b]**Simriz**: *similar to PTFE with wider uses/applications.*

6.6.0 Installation Details

Installation of the meter is similar to installation of other PD meters already discussed. A few pertinent points for oscillating piston disks are enumerated below:

1. **General:** Common installation requirements of PD meters such as the use of isolating and bypass valves to allow filter cleaning or flow meter, etc. already discussed are also applicable here. Some related issues are discussed below. These are discussed in connection with this meter but depending on applicability could be utilized for other PD meters also.
2. **Piping configuration:** There should be a minimum clearance between the meter and the filter (with recommended mesh size) to be maintained in line with the manufacturer's recommendation. The piping configuration as shown in connection with other PD meters is also applicable. The flow meter should be located at the discharge of the pump. This issue is similar to that discussed in Subsections 2.4.1 and 2.4.2. Also, in utility applications the piping configuration should be as shown in Fig. IV/2.4.0-3. Some typical piping configurations for installations are depicted in Fig. IV/6.6.0-1. This is similar to what has been mentioned earlier, with the only difference being that in this figure bidirectional flow has been shown. For bidirectional flow applications, use a filter on each side of the flow meter. Such a configuration is applicable to other PD meters also.
3. **Common installation issues:** These are a few installation issues to be looked into, including:
   - The meter shall be mounted as per flow direction.
   - When vertical mounting is allowed, the flow should be from the bottom to the top.
   - The meter shall be at a pump discharge and in all cases the meter should be free from any stress/strain and vibration.
   - Reciprocating piston meters with inline ports should have the transmitter either on the side or upside down, but for very high-pressure versions, the transmitter should be on top [17].

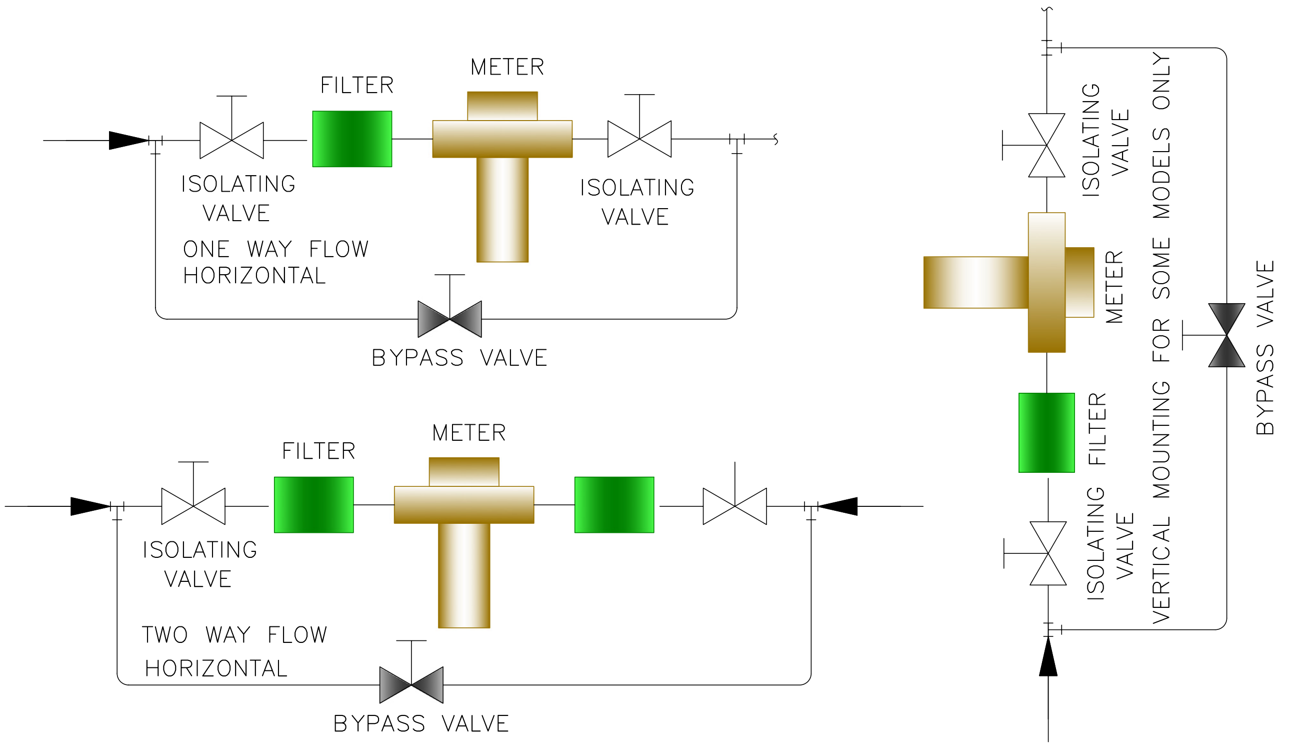

FIGURE IV/6.6.0-1 Reciprocating piston meter installation.

- Meters with SAE fitting (¼″) should have an o-ring fitting attached to the meter that is always lubricated [17].
- When integral mounted electronics are used, care should be taken to ensure that it is not subjected to a temperature beyond the limit mentioned in the manual.

7.0.0 MISCELLANEOUS POSITIVE DISPLACEMENT FLOW METER TYPES

There are many types of positive displacement flow meters, of which some types have been covered in the above discussions. A few other types which are also used in plant flow measurement and control are discussed briefly in the following sections.

7.1.0 Lobed Impeller PD Meter

There are some similarities between an oval gear meter and a lobed impeller PD flow meter.

7.1.1 OPERATING PRINCIPLES OF LOBED IMPELLER PD METERS

In the case of a lobed impeller meter there are two 8-shaped lobed impellers which rotate in opposite directions to the flow exerted by the fluid flow, within the measuring chamber, as shown in Fig. IV/7.1.0-1. Each rotation creates four crescent-shaped fixed volume, so, on account of lobed impeller rotations, a fixed volume of fluid is expelled. A gear train external to the chamber synchronizes and maintains the fixed relative position of the lobed impellers. Therefore, the number of rotations of the impellers is proportional to the volume flow through the meter. The impeller rotations are transmitted to the register with the help of the gear trains mentioned above. Proximity switches and/or other magnetic pick ups are used to sense the rotation to generate output pulses and drive the electronic registers.

7.1.2 OPERATING CONDITIONS AND AVAILABLE SIZES OF LOBED IMPELLER PD METERS

Normal operating conditions and available meter sizes are:

1. **Pressure-withstand capability:** Up to 200 kg/cm^2;
2. **Temperature-withstand capability:** up to 300°C;
3. **Flow range:** 30–66,000 L/min;
4. **Meter sizes:** 50–600 mm NB;
5. **Materials:** A wide range of materials to support high pressure and temperature. Impellers are made of corrosion-resistant thermoplastics [7] to protect from abrasion and wear and tear.

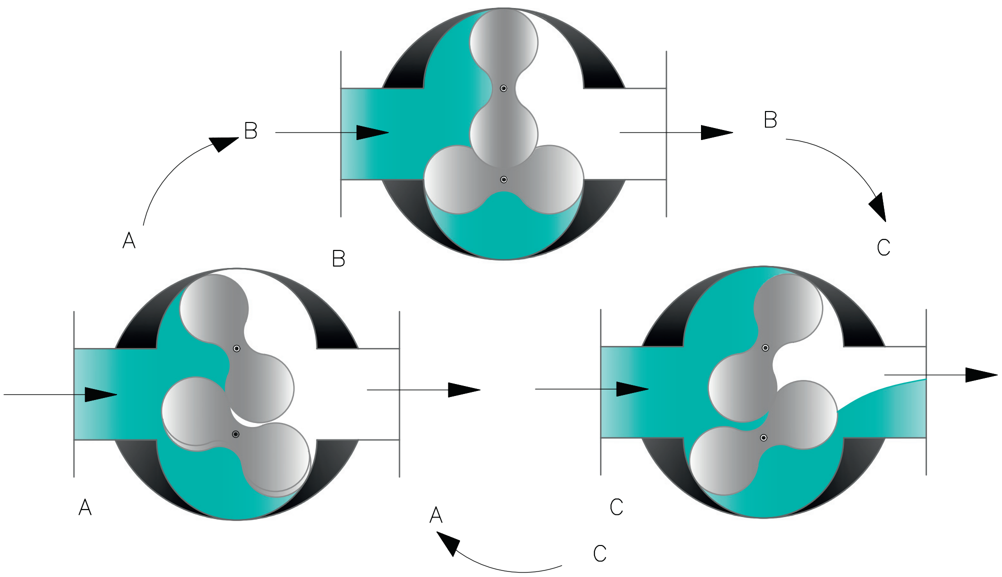

FIGURE IV/7.1.0-1 Lobed impeller meter.

7.1.3 PRESSURE LOSS PERFORMANCE AND USAGE

Typical pressure loss in this meter, under normal operating conditions, is depicted in Fig. IV/7.1.3-1. The meter can offer high performance with high repeatability and accuracy of +0.15% AR. These meters can be used for LPG to very highly viscous fluid and gas.

- Sluggish response for quick change in differential pressure;
- Change in viscosity greatly affects performance;

The discussion on lobed meters is now concluded and we now turn to gear type meters.

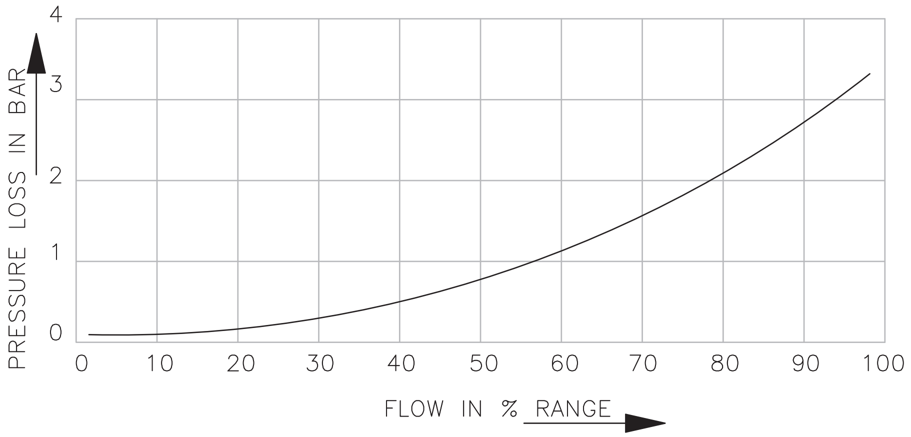

FIGURE IV/7.1.3-1 Pressure loss for lobed impeller meter.

7.1.4 MAJOR ADVANTAGES AND LIMITATIONS

1. **Advantages:** Like other PD meters this meter does not require external power and does not have requirements for straight length. The following are major specific advantages of these meters:
   - Excellent accuracy in gas measurement;
   - Overall performance is good;
   - Only two moving parts, hence less wear and tear;
   - Approved by weights and measurements.
2. **Disadvantages:** Like other PD meters it can operate with clean fluid only as solid particles can block the meter. Additional limitations are as follows:
   - Low accuracy at low-flow conditions;
   - Heavy and costly;
   - Too much pulsation due to alternate drive action [13];

7.2.0 Helical Gear PD Meters

Short discussions on helical gear meters have been presented in Section 3.1.2.5 in Chapter I. Here the same will be discussed in greater detail.

7.2.1 OPERATIONAL DETAILS

Helical gear PD meters use two nos. of well-nested helical gear types rotor arrangement inside the measuring chamber as shown in Fig. IV/7.2.0-1. They operate like a screw to draw and divide a fixed volume of the fluid from the inlet

FIGURE IV/7.2.0-1 Helical gear PD meter.

and expel the same through the meter outlet. This resembles a screw conveyor. The rotors' axis and orientation are in line with the fluid flow path. The rotor can rotate at a high number of revolutions to cover a wide flow range. It can cater to high-viscosity applications. On account of the close machining tolerances between the two sets of helical gear, leakage through the meter is reduced to ensure better accuracy. These PD meters offer a comparatively lower pressure drop. Available design variations include versions that are heated to maintain line temperatures for metering melted solids or polymers [7].

7.2.2 OPERATING CONDITIONS AND AVAILABLE SIZES OF HELICAL GEAR PD METERS

Normal operating conditions and available meter sizes are enumerated below:

1. **Pressure-withstand capability:** Up to 200 kg/cm^2;
2. **Temperature-withstand capability:** up to 300°C;
3. **Viscosity range:** <1500 cP;
4. **Flow range:** 20–15,000 L/min;
5. **Meter sizes:** 40 to <300 mm NB;
6. **Materials:** A wide range of materials are used to support the high pressure and temperature.

The meter can also be deployed for slurry services. Like other PD meters these meters should be used with standard accessories such as filters, etc.

7.2.3 PERFORMANCE

1. **Accuracy:** 0.5%–0.2% AR;
2. **Repeatability:** 0.5% FSD;
3. **Turndown:** 100:1.

7.3.0 Gear PD Meter

Gear-type PD meters are similar to the gear pump, with the difference being that in the case of the pump, the gears drive the fluid, whereas in case of the gear PD meter fluid drives the gear sets.

7.3.1 OPERATING PRINCIPLES OF GEAR PD METERS

In gear PD meters there are two round gears mounted in the measuring chamber. On account of the differential pressure, the fluid drives the gears, each of which rotates in opposite directions as shown in Fig. IV/7.3.0-1. So, for this rotation, the measuring fluid trapped in the voids of the gear teeth is transported from the inlet port to the outlet port. As the gears are symmetrical a fixed volume of fluid is trapped and passed through. On account of symmetry it is possible to measure bidirectional flow. In the case of bidirectional flow measurement accessories and configuration, etc. are similar to Fig. IV/6.6.0-1. Horizontal mounting is acceptable but vertical mounting may also be possible, depending on the condition and meter chosen. Gear combination is at the heart of the system and to prevent wearing of the same, wear-resistant materials are used to ensure a longer life. When the gear passes the sensor a train of pulses is generated as each gear tooth passing the sensor square results in a pulse being generated. Normally, magnetic/Hall effect sensors are used to sense the gear rotation.

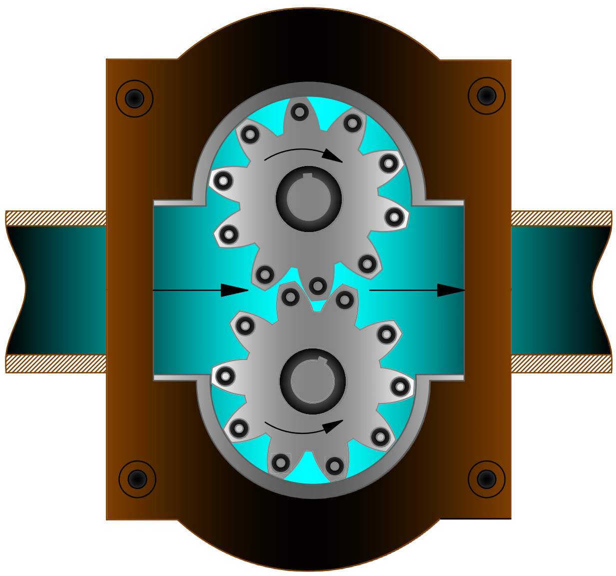

FIGURE IV/7.3.0-1 Gear PD meter.

7.3.2 OPERATING CONDITIONS AND AVAILABLE SIZES OF GEAR PD METERS

The normal operating conditions and available meter sizes are:

1. **Pressure-withstand capability:** Up to 300 kg/cm^2 [19];
2. **Temperature-withstand capability:** up to 200°C;
3. **Viscosity range:** <1500 cP;
4. **Flow range:** 0. 1 to 100 LPM;
5. **Meter sizes:** 6 to >100 mm NB [19].

7.3.3 BRIEF SPECIFICATION

1. **Materials:** A wide range of materials are used to support the high pressure and temperature conditions, such as aluminum, SS316, etc;
2. **Output:** pulse analog 4–20 mADC;
3. **K factor:** wide range 420–14,000 pulse/L;
4. **Process connection:** Screwed type in different sizes;
5. **Performance data:**
   - *Accuracy:* ~0.2% AR or better;
   - *Repeatability:* 0.2% FSD or better.

7.4.0 Rotary PD Meters

7.4.1 DESCRIPTION OF ROTARY PD METER

A rotary meter is another kind of PD meter. This flow meter has one measuring chamber in which there are two types of rotating elements, i.e., one larger blocking rotor and two displacement rotors—the direction of rotation of blocking rotor is in opposite to the direction of rotations of displacement rotor. The rotation of all of these three rotating items is maintained and synchronized by matching gears. Combined rotation of these three rotating elements divides the measuring chamber into a fixed volume and after one complete rotation a set volume is delivered to the outlet port. As shown in Fig. IV/7.4.0-1, the fluid enters the chamber from one side (left-hand side) and the blocking rotor is forced to rotate due to differential pressure. As the displacement rotors are connected via gears, they also rotate to facilitate the flow of fluid through the chamber to the outlet. Thus rectilinear flow is translated into rotary motion inside the meter.

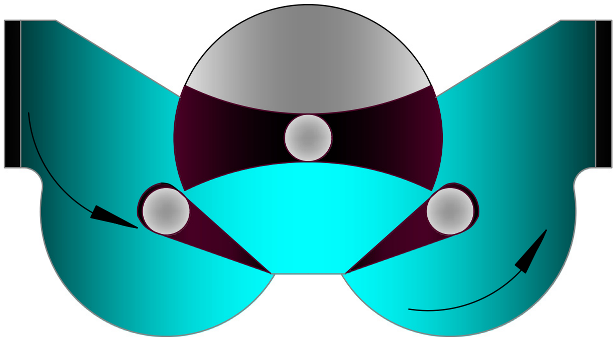

FIGURE IV/7.4.0-1 Rotary type PD meter.

The rotation of the blocking rotor is picked up by a magnetic/Hall sensor for transmitting the same to the register. There is very little clearance between the chamber and rotors, therefore, it is necessary that the meter be properly applied for the flow rate and operating pressure of the system [20]. There could be as many as six phases of positional changes in these rotors for drawing fluid in and driving the same out. On account of this and the single chamber construction, the meter has low pressure loss. However, calibration of the meter is an important issue.

7.4.2 BRIEF SPECIFICATION OF ROTARY METERS

The normal operating conditions and available meter sizes are listed here:

1. **Pressure-withstand capability:** Up to 10–15 kg/cm^2;
2. **Temperature-withstand capability:** (–) 20–80°C;
3. **Flow range:** 0.1 to1100 LPM;
4. **Meter sizes:** 50–80 mm NB;
5. **Process connection:** NPT/BSP thread/flange connection;
6. **Construction materials:**
   - *Housing/rotor:* Anodized aluminum, ductile iron/stainless steel;
   - *Rotor journal:* Plated stainless steel;
   - *Bearing plate/timing gear:* stainless steel;

7. **Performance specification:**
   - *Accuracy:* 0.1% FSD;
   - *Repeatability:* 0.15% FSD.

Normally PD meters are used with standard accessories such as an air eliminator, strainer, shutoff valve, etc. In the following section these accessories are discussed briefly.

8.0.0 PD METER ACCESSORIES

From the above discussions it is evident that for proper functioning of PD meters, a number of accessories are necessary. The discussions on positive displacement meters conclude with short discussions on the accessories commonly used for PD meters. Common and standard accessories for positive displacement meters include:

- Strainer/filter to remove solids;
- *Air eliminator:* eliminates air and gases;
- *Shutoff valves:* for control;
- Temperature compensator;
- Analog/pulse/smart transmitter;
- Local and remote registers.

It is worth noting that a few items such as a flow indicator, totalizer, and batch controllers are separately discussed in Chapter XI, therefore, only brief discussions have been presented here. *Various data presented here in generalized forms are from reputed manufacturers and for most available accessories. There may be some variations with actual accessories for any particular device/meter.*

8.1.0 Strainer/Filter

For PD meters strainers are always recommended at the inlet side of the meter as protection against damage/blockage due to solids and foreign particles (e.g., rust, pipe-burrs/scale) in the liquid. Strainers help to increase the service life of the meter. Normally it is recommended that systems should be cleaned periodically. There could be various types of filters such as Y type or basket filter. In some cases high-capacity strainer and air eliminator combinations are also available. Basket filters are available for LPG, gasoline, solvent heating oil, diesel, and other motor fuels.

8.1.1 STRAINER/FILTER SPECIFICATION

The major specifying issues are as follows:

1. **Size:** 50−150 mm NB;
2. **Pressure rating:** >20 bar;
3. **Typical mesh sizes:** 30 (25−40) μm;
4. **Materials:** Brass/aluminum/stainless steel.

8.2.0 Air/Vapor Eliminator

Air eliminators are installed at the inlet of the meter for liquid services. The main purpose of an air eliminator (sometimes in the downstream with an air check valve) is to eliminate/minimize the passage of air/vapor through the meter for precision flow measurement. This is essential for dispensing the system. As the air or vapor release will contain a small amount of liquid, it should be vented back to a storage tank or special catchment tank/arrangement. Air eliminators are based on a float valve design. The air eliminator housing contains a float assembly, flexible reed strips, and two orifice plates to control elimination of free air or vapor. Optical vapor eliminators without any moving parts are available for refined petroleum products [21]. Use of air/vapor eliminator is also requirement for weights and measures. The following are major specification issues:

1. **Size:** 50−150 mm NB;
2. **Pressure rating:** >20 bar;
3. **Material:** Brass/aluminum/stainless steel/cast iron;
4. **Type:** Air eliminator/vapor eliminator/eliminator strainer/bulk eliminator.

8.3.0 Shutoff Valve

A shutoff valve is often needed for meter operation to avoid overspeeding. Apart from avoiding overspeeding they are also used for various control functions. There are a wide range of

valves used in connection with PD meters, including a mechanically actuated manual valve at the outlet of the meter. These could be used as an isolation valve as well as they could be connected through a mechanical linkage/hydraulic circuit to a mechanical preset counter. Also, it could be a solenoid-operated control valve connected to, e.g., an electronic preset counter. Differential valves for LPG applications are used to stop liquid flow in the case that vapor is present. Other valve types include but are not limited to the following:

- Ball check valve;
- Digital valve;
- Air check valve;
- Control valve;
- Spring-loaded check valve;
- Solenoid-operated control valve (refined petroleum product);
- Air-activated differential check valves.

There are many types of valves, normally available in sizes from 1½″ to 4″. Materials used are mostly aluminum/stainless steel, but other materials are also available. They are intended to withstand high pressures up to 20 bar.

8.4.0 Temperature Compensator

Not all, but many, PD meters have a built-in temperature compensation unit. Often these are available as separate accessories. Temperature compensators provide net volume or weight registration based on the continuous integration of gross metered volume, by duly compensating for the temperature fluctuation (and thereby volumetric expansion of liquid). These are available for electronic compensations as well as mechanical liquid-filled bulbs. For electronic compensations, RTDs with an SS thermowell are available.

8.5.0 Analog/Pulse/Smart Transmitter

The basic purpose of a transmitter is for remote transmissions. These could be pulse type, analog type, or smart type (to support HART protocol, Fieldbus systems such as Profibus). These transmitters additionally perform a linearization function (up to, e.g., 10−15-point linearization), compensation functions, or an antidither buffer (masks false output), etc. These are all electronic transmitters. There are various kinds of transmitters available to convert mechanical movement into electrical pulses and/ or to generate proportional 4-20 mADC analog output as discussed in section 8.5.2. Various technologies are involved in this and some of include, but are not limited to:

1. Mercury-wetted switch type;
2. Dry pulse Reed type (10:1);
3. Solid state (100:1) type;
4. Photoelectric rotary;
5. Infrared type.

8.5.1 PULSE TRANSMITTER

Pulse transmitters are often used to communicate with PLC/DCS or computer systems accepting pulse input for rate flow as well as totalized flow computation. The K factor of the meter determines the number of pulses per unit flow. Normally the pulse outputs are in voltages in the range of 5−30 VDC. These are usually housed in aluminum/ABS housings and mounted with the meter. Most are also certified by the appropriate authority for use in hazardous environments.

8.5.2 ANALOG/SMART TRANSMITTER

Basically, analog transmitters are electronic converters converting a pulse signal into an analog transmission signal of 4−20 mADC. Normally these are operated by 24 VDC (18−30 VDC) supply voltage. They are also used with input signal filtering. To keep pace with modern technologies many of these meters are now available with smart transmitters supporting HART protocol and fieldbus systems detailed in Chapter XI.

8.6.0 Local and Remote Register

Positive displacement flow meters are basically volumetric flow meters, so volume registers are

part and parcel of the meter. There are two kinds of registers, mechanical registers which are generally fitted with the meter for local volume register and the other type is electronic and is mainly used for remote volume registering. However, totalizing is not the main function of a register, this would be a preset counter, ticket printer, etc.

8.6.1 LOCAL REGISTER (MECHANICAL)

Based on their functions, registers include:

1. **Mechanical counter:** Large numeral resettable/nonresettable;
2. **Mechanical counter with ticket printer:** as above with printing facility as a record of the transaction;
3. Combined rate indication and mechanical counter;
4. Mechanical preset counter for valve operation at predetermined volume;
5. Counter-mounted pulser for remote use;
6. Mechanical rate-of-flow indicator for local flow rate;
7. Combined rate indication and mechanical counter.

8.6.2 REMOTE REGISTER (ELECTRONIC/DIGITAL)

Compared to mechanical registers, electronic digital registers provide much better accuracy, productivity, and security. Digital electronic registers offer a resettable and totalizer display, preset valve control function, and many other enhanced functions such as date and time stamping, point-of-sale (POS), automated data collection, product selection, linearization, compensated volume computation, on-site ticket generation, auto-batch, data management, route control, and GPS communication facility with built-in security features. Most are compatible with all types of PD flow meters and are available in weather-proof systems, such as NEMA 4X or IP66/67. Certification from appropriate authorities may be available for use in hazardous atmospheres. Some of these types and their features are as follows:

1. **Simple electronic registers:** To ease product handling simple commands such as "RUN," "STOP," and "PRINT" are built in. Some are provided with aviation fueling functions also.
2. **Data management system (DMS):** The DMS is an in-cab data management system designed for fuel delivery systems and vehicles. It is also suitable for aviation fuelling systems [21].
3. **Differential pressure (DP) transducer:** A safety shutdown device used in aviation fuelling.
4. Large LED remote display.

9.0.0 FLOW SENSING

During the discussions on various types of meters, magnetic and Hall effect sensors were mentioned for PD meters. Both of these are used quite frequently. In this section discussions will be mainly concentrated on Hall effect sensors. Magnetic pick ups have been discussed at length in Chapter V in connection with turbine flow meters. Similar pick ups are also utilized here so this discussion is not repeated here, the reader may refer to Chapter V for this. The discussions here start with the Hall effect. Detailed account on various sensing methods have been covered in chapter X. This part should be read in conjunction with chapter X. Here in order to complete the discussions basics of Hall Effect has been discussed.

9.1.0 Hall Effect Sensing

In 1870 Edwin Hall discovered this phenomenon in semiconductors and so the effect was named after him. When a thin piece of rectangular p-type semiconductor material, such as gallium arsenide (GaAs), indium antimonide (InSb), or indium arsenide (InAs), carrying a continuous current through it is placed in a magnetic field perpendicular to the direction of current through the thin plate as shown in Fig. IV/9.1.0-1, then the flux will exert a force (Lorentz effect) on the

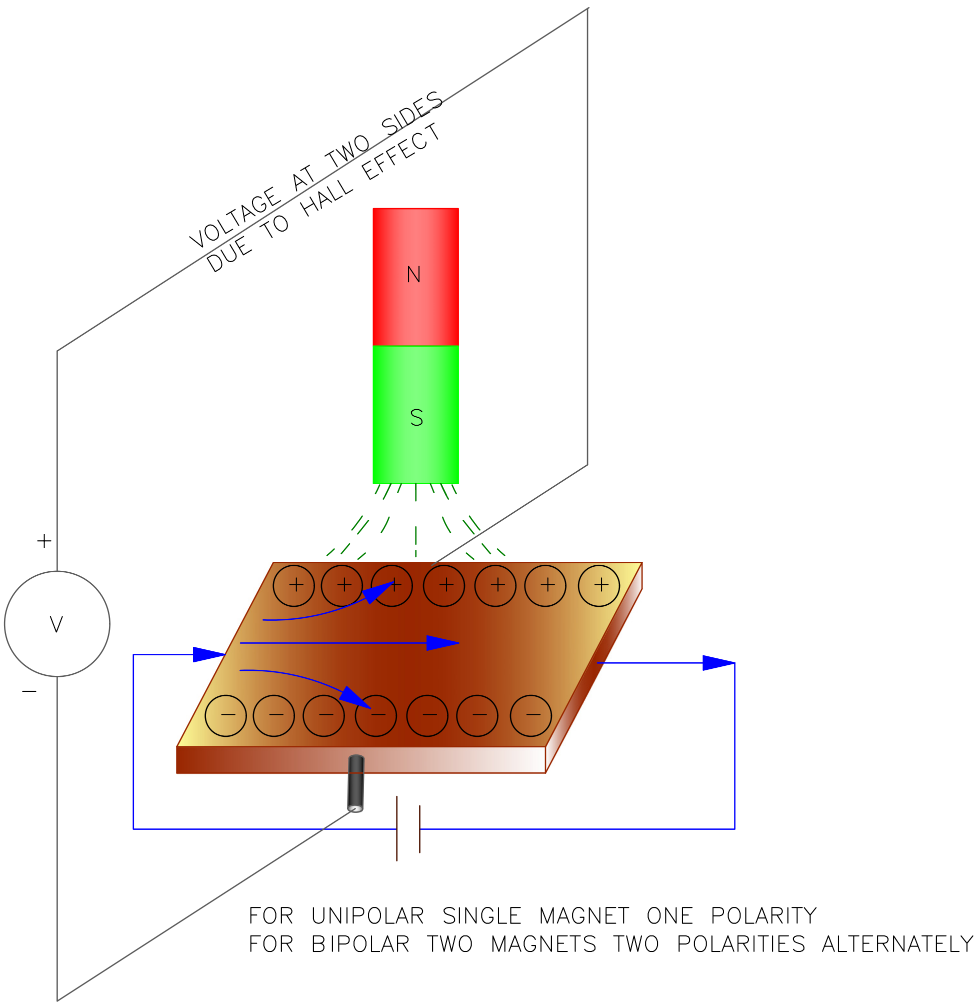

FIGURE IV/9.1.0-1 Hall effect sensing.

semiconductor material. On account of this force due to magnetic flux, the charge carriers will migrate to the two sides of the rectangular semiconductor plate. Charge carrier electrons and holes will be deflected in opposite directions. Therefore, as these electrons and holes move to opposite sides, there will be a potential difference between the two sides of the semiconductor material by the build-up of these charge carriers. Voltage will therefore develop between the sides, perpendicular to both the direction of current as well as to the direction of the magnetic field. This effect of generating a voltage in the presence of a magnetic field is called the Hall effect. This type of voltage sensing can be analog or digital. Currently, digital output sensors with square wave output/digital output are most commonly used. Hall effect sensors can be bipolar, using the south pole to operate them and the north pole to release them. In unipolar sensors only a south pole is required to operate them, whereas for bipolar applications both poles are required to operate and release them, respectively. In flow applications, such as PD meters and/or turbine meters, the interruption of the magnetic field due to movement of vanes/impellers or turbine blades helps to generate square waves. Depending on the utilization of a single south pole and/or both poles, square pulses can be unipolar or bipolar pulses.

9.2.0 Hall Effect Flow Sensors

Hall effect sensing, as described above, is very versatile and used widely as a sensor in positive displacement meters and many other meters (e.g., turbine meters). The magnets in the impellers of a positive displacement flow meter or, for example, a blade in a turbine rotor, are used to trigger the switching circuit in the sensing system in conjunction with associated preamplifying or signal-conditioning circuits transmitting a square-wave pulse to any connected signal conditioner/monitor/control circuitry. These flow-sensing systems are meant to be used in a broad range of input frequencies and operating conditions. For Hall effect sensors, it is necessary to ensure that requisite external power is available. Hall effect sensors are very popular when square-wave pulse output is necessary. Hall effect sensors are recommended when the output frequency from the meter over any part of the application flow range is 10 Hz or less. The following are a few features of this sensing system:

1. Digital logic compatibility;
2. **Good turndown ratio:** 10:1;
3. Quicker installations;
4. NEMA 4/IP65 enclosure possible;
5. Wide range of operating and environmental temperatures;
6. Acceptable for safety applications with certification.

Hall effect flow sensors are widely used in many other flow metering applications other than positive displacement meters. For further details Chapter X may be referenced.

With this the discussions on positive displacement meter come to an end; discussion now centers on flow metering based on velocity and force.

LIST OF ABBREVIATIONS

ABS Absolute
AR Actual reading (in connection with accuracy)
CHU Constant head unit
DP Differential pressure
DPT Differential pressure transmitter/transducer
EGL Energy grade line
ETFE Ethylene tetrafluoroethylene (type of plastic)
FSD Full scale division (in connection with accuracy)
FTR Flow turndown ratio
HFO Heavy fuel oil
HGL Hydraulic grade line
ID Internal diameter
LHS Left-hand side
LIE Local instrument enclosure
LVDT Linear variable differential transformer
MTR Measurement turndown ratio
NB Nominal bore
OD Outer diameter
PVDF Polyvinylidene fluoride—plastic type
RF Raised face or radio frequency
RHS Right-hand side
RTJ Ring tongue joint
RTD Resistance temperature detector
SIL Safety integrity level
SS Stainless steel
US Ultrasonic/United States
USRB United States Bureau of Reclamation
VM Valve manifold
VTR Viscosity turndown ratio
WRT With respect to

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CHAPTER V

VELOCITY AND FORCE TYPE FLOW METER

Chapter Outline

Plant Flow Measurement and Control Handbook. https://doi.org/10.1016/B978-0-12-812437-6.00005-6

1.0.0 INTRODUCTION

In this chapter, discussions will be put forward on velocity-sensing flow meters and flow meters working on force applied in a flow meter in sequence. Under velocity type flow meters there are a few different flow meter technologies that are deployed. Naturally, velocity type flow meters can be classified in different classes as discussed in the following sections. On the other hand, under force type flow metering, target flow meters are covered.

1.1.0 Velocity-Sensing Flow Meter: Introduction

During the initial discussion, it has been noted that in a closed conduit, area (known) multiplied by velocity will dimensionally give the volume flow rate, i.e., volume change per unit time. So, in flow meters where velocity is sensed, it gives the volume flow rate as long as the area of the closed conduits is fixed. From this volume flow mass flow can be *computed* by considering the density effect at operating temperature—pressure conditions. Velocity-sensing flow meters can be classified as:

- **Inferential type:** e.g., turbine, impeller type, propeller type;
- **Oscillating type:** swirl/vortex type;
- **Fluidics type:** Coanda effect and momentum exchange;
- **Electrical type:** electromagnetic FM, ultrasonic FM.

The above classifications are important in the sense that each of these types of meters has different characteristic features and requires different treatment and associated discussions. In this chapter all these types of flow meters will be discussed. In addition, anemometers, another velocity type flow measurement, and target flow meters, in which flow is sensed by force, will also be covered. Flow meter selection has been discussed at length in Section 4.0.0 (Tables I/4.2.2.8-1 and I/4.5.0-2) of Chapter I. Now short general characteristic features of a few important velocity and force type flow meters are presented below along with their usage to enable the reader to get an idea of the meter types. (*Here the following abbreviations have been used. EMFM: Magnetic: electromagnetic; US: ultrasonic; ID: pipe internal diameter (D): straight length specified as multiple of pipe ID.*)

1. **Fluid type:**
   - *Clean liquid:* turbine, vortex/swirl, target, magnetic, US (transit);
   - *Dirty liquid:* magnetic, US (Doppler);
   - *Corrosive liquid:* magnetic;
   - *Slurry:* magnetic;
   - *Vapor/gas:* turbine, vortex/swirl, target.
2. **Span ratio (min/max) [1]:**
   - *Turbine:* 1:5/1:20;
   - *Vortex/swirl:* 1:15; 1:20;
   - *Magnetic:* 1:50;
   - *Ultrasonic:* 1:10.
3. **Available sizes:**
   - *Turbine:* 6—600 mmNB;
   - *Vortex/swirl:* 15—400 mmNB;
   - *Magnetic:* 6—3000 mmNB;
   - *Ultrasonic:* 15—3000 mmNB.
4. **Pressure rating PN:**
   - *Turbine:* 100 (ANSI600);
   - *Vortex/swirl:* 100 (ANSI600);
   - *Magnetic:* 250 (ANSI1500);
   - *Ultrasonic:* 100 (ANSI600).
5. **Temperature withstand capacity:**
   - *Turbine:* 300°C;
   - *Vortex/swirl:* 300°C;
   - *Magnetic:* 200°C
   - *Ultrasonic:* 200°C;

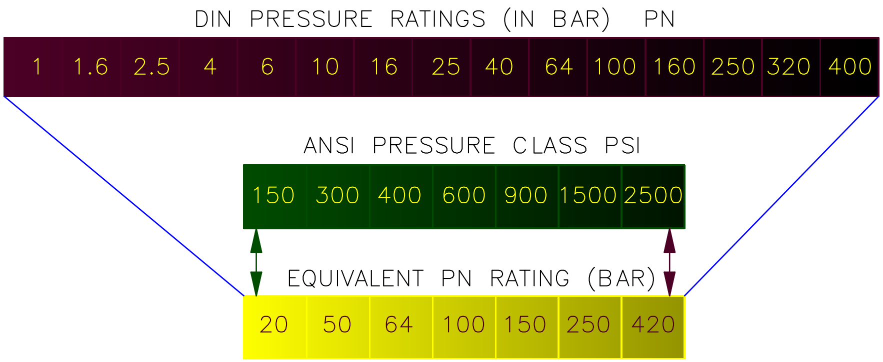


FIGURE V/1.0.0-1 PN-ANSI equivalence.

6. **Typical straight length (up/downstream):**
   - *Turbine:* 15/5 ID;
   - *Vortex/swirl:* 15/5ID (swirl less: 3/1ID [1]);
   - *Magnetic:* 4/2 ID;
   - *Ultrasonic:* not affected.
7. **Process connection:** flanged normally.

DIN pressure ratings are pressure number (PN). In ANSI pressure ratings are mentioned as psi. The equivalence between them has been given in Fig. V/1.0.0-1.

In PD meters there are some commonalities (such as definite volume of fluid, no external power requirement) amongst various types of PD meters. As in velocity type flow meters, different classes use different technologies, so such commonalities are not possible. So, starting with inferential meters different classes will be discussed separately.

1.2.0 Turbine, Paddle Wheel, and Other Inferential Flow Meters

As the name suggests inferential flow meters operate on the basis of calculating/computing volumetric flow rate by measuring some property of the flow stream.

1. Truly speaking, the head type meter is also an inferential flow-measuring system. Since the head type flow measurement system has the largest market share of flow meters and is the most common and old system, it is normally treated separately under head type measurement (as has been done in this book in Chapter II).
2. The other most common type of inferential flow meter is the turbine meter—a loosely used term for an inferential flow meter. However, other than turbine meters, there are other types of inferential flow meters also. These inferential meters have rotor-mounted blades which are rotated by the fluid at a rotational speed proportional to the flow rate. The revolutions of these blades are monitored directly or through a gear train with the help of magnetic/optical and other types of pickups. These inferential flow meters, to be specific turbine meters, give very high accuracy and are often chosen for custody transfer operations in the oil and petroleum industries.
3. Of the many types of inferential velocity type flow meters, turbine meters are the most commonly used in industry. Therefore, the major thrust of discussions will be on these. At the end of the chapter other types will be also covered.

1.3.0 Oscillating Type Flow Meters

In an oscillatory flow-measuring system, oscillatory motion of the fluid is created on account of primary flow elements/device. The frequency of such oscillation is detected by a secondary measuring device to produce an output signal proportional to the fluid velocity. Vortex, earlier vortex precession (swirl) meters, and Coanda meters fall under this category.

1.4.0 Fluidic Flow Meters

Momentum exchange and Coanda effect flow meters also utilize fluidic properties (Fig. I/3.1.3-8), therefore in this book these have been categorized as a separate class of fluidic meters.

1.5.0 Electrical Flow Meters

In this type of flow meters electrical properties are utilized to measure the flow. Electromagnetic flow meters and ultrasonic flow meters (transit time and Doppler type) fall under this category of meter. In electromagnetic flow meters, minimum conductivity of fluid is necessary, to develop electromagnetic induction following Faraday's law of electromagnetic induction (to measure the process flow). In an ultrasonic flow meter the velocity of a fluid is measured with the help of ultrasound energy.

1.6.0 Force Type Flow Meters

In this category flow is measured with the help of an impact force on the target element. The target flow meter utilizes this principle.

In this chapter these will be discussed sequentially. The discussion starts with turbine, paddle wheel, and other inferential flow meters in the following section.

2.0.0 TURBINE, PADDLE WHEEL, AND OTHER INFERENTIAL FLOW METERS

In this section discussions cover turbine flow meters, paddle wheel flow meters and other inferential flow meters.

2.1.0 Descriptive Details of Turbine Flow Meters (TFMs)

Turbine meters measure volume flow indirectly by measuring the number of revolutions, so these are inferential meters. Following the principles of a turbine, a turbine meter is basically an instrument where the kinetic energy of a moving fluid is converted into rotational energy. In a turbine meter, when fluid flows through the meter it impinges upon multibladed rotor on a free-running bearing. A multibladed rotor suspended in fluid and bearings are free to rotate about an axis along the centerline of the meter body. The angular (rotational) velocity of the turbine rotor is directly proportional to the fluid velocity through the turbine. The governing flow equation can be given by

$$q = \frac{\bar{r}A\omega_i}{\tan\bar{\beta}} \qquad \text{(V/2.1.0-1)}$$

where, q is the fluid volume flow rate; r is the average radius of rotor; A is the annular flow area, ω_i angular velocity and the blade angle is represented by β. Here, parameters, r, A, and β are constant for a turbine design. Therefore, it is clear that in an ideal situation, $q \propto \omega_i$.

In the real situation, there will be slippage of the rotational speed, due to the development of a retarding torque at the rotor [2]. This retarding torque comes from:

- **mechanical friction:** bearing friction and mechanical loading on flow register;
- **fluid forces:** viscosity drag—a function Reynolds number and turbulence (velocity) (Chapter I).

The basic principle of operation of a turbine flow meter has been covered in Subsection 3.1.3.1 of Chapter I. Therefore, this discussion starts with a short recapitulation of the principles of operation of the same with some extra detail.

2.1.1 PRINCIPLE OF OPERATION OF TFMs

From the above discussion, it is clear that when there is flow through the pipe the multibladed rotor assembly suspended in the pipe fluid with its face perpendicular to the fluid flow, the rotor starts rotating at a rotational speed proportional to the flow velocity. The rotational speed is monitored by pickup, mounted on the meter body outside the meter wetted part housing. There are

various types of pickup, such as reluctance, inductance, and photoelectric types. Normally the output signals from these pickups are pulses whose frequency is proportional to the flow rate. These pickups offer good accuracy and rangeability. Another important issue is that these pickup output pulses can be produced for a small incremental volume of flow. The turbine meter and associated digital electronics form the basis of any liquid metering system as the incremental outputs are in digital form [3] so resolution of signal could be very precise.

2.1.2 DESCRIPTION OF A TURBINE METER

As indicated above, the turbine meter comprises an axially mounted multibladed rotor assembly suspended in fluid within the meter body, with its face perpendicular to the direction of fluid flow. The multibladed rotor is run by the fluid flow. The assembly runs on bearings and is mounted concentrically within the flow stream by means of upstream and downstream supports as shown in Fig. V/2.1.0-1.

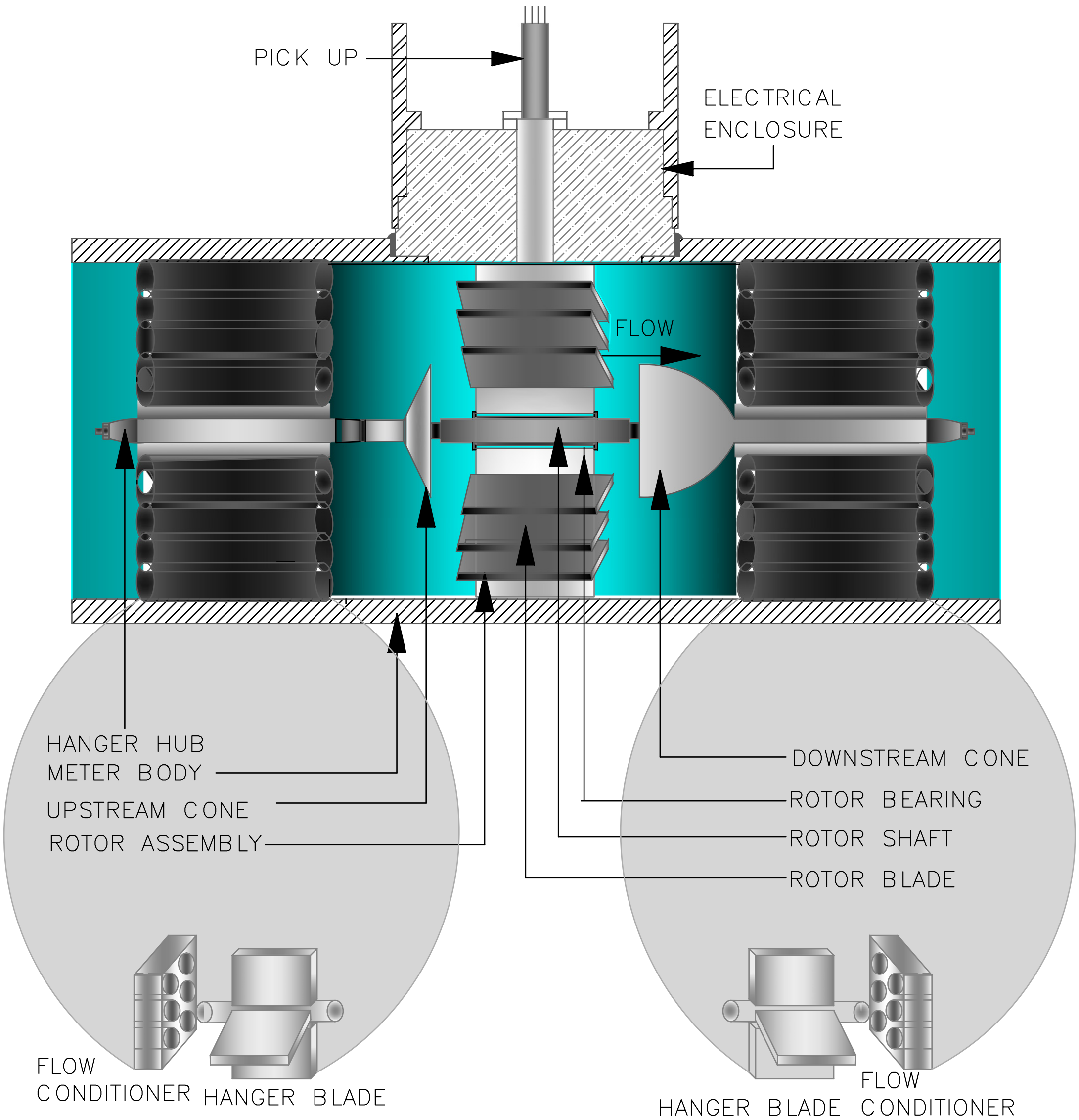


FIGURE V/2.1.0-1 Turbine flow meter GA. *Developed based on an idea from Daniel™ Liquid Turbine Flow Meters, Technical Guide, Daniel—Emerson, April 2015. http://www2.emersonprocess.com/siteadmincenter/PM%20Daniel%20Documents/Turbine-Meter-Tech-Guide.pdf.*

To get better performance and less distortion of flow profile (discussed later) normally flow conditioners are used at the upstream and downstream of the meter. In many meters (e.g., liquid flow meter from Daniel–Emerson Series 1500/1200) in addition to flow conditioners there are hanger blades mounted on hanger hubs. These hanger assemblies are put both upstream and downstream, as shown in Fig. V/2.1.0-1. Based on the difference in rotor and bearing design there are different turbine flow meter types and styles. Depending on the design, the rotor assembly consists of 12–16 blades in liquid applications and a hub where blades are locked. The number of blades in the case of a *gas* application will be closer to 25–30. As stated above, this hub runs on a bearing. For fluids with lower viscosity in the range of 5 cSt or less and specific gravities of less than 0.70 [3], the rotor may not need a rim. However, for high-viscosity fluids and/or higher meter sizes, rims are used to get better rigidity. The flowing fluid enters the turbine through the forward conditioner and/or hanger blades (on a hanger hub). These are used to improvise the flow profile and guide the flow stream parallel to the meter center line. After this it encounters the sharp angle of the upstream cone, where the streams lose pressure and gain velocity. Also, the stream is deflected. The pressure reaches the minimum point in the rotor and the velocity becomes very high. At the rotor the kinetic energy of a moving fluid is converted into rotational energy. As the fluid leaves the blade area, flow is redistributed with the help of a downstream cone. At this point there will be pressure recovery and velocity is reduced proportionately, as shown in Fig. V/2.1.0-2. The output frequency is dependent on the blade angle of the rotor. There are two other important points to be noted:

- The upstream cone is sharper and causes quick pressure reduction, in contrast the downstream cone is smoother to help with smoother pressure recovery.
- On account of the differences in pressure and velocity, there will be a tendency for the rotor to shift towards the upstream thrust, an offset is maintained to overcome this.

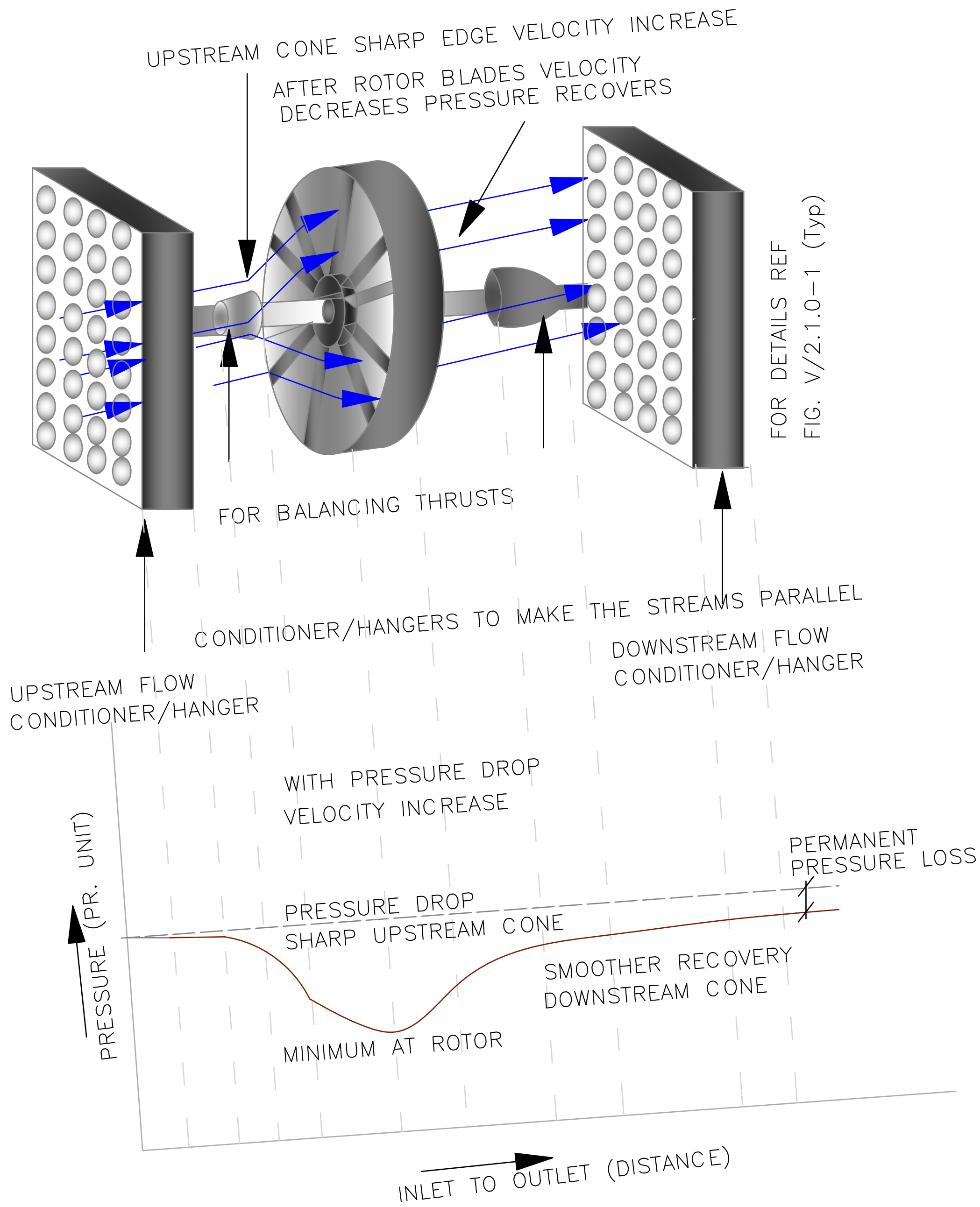
The cross-sectional area of the cone is slightly smaller than that of the rotor hub, with some flow impinging directly upon the rotor hub, generating a downstream thrust [3]. In this way balance is maintained.

In the case of bidirectional TFM there have to be two sharp upstream cones at the two sides of the meter. The major parts of TFM normally include the following:

1. Meter body;
2. Flanges for process connection;
3. Threaded electrical connector;
4. Flow conditioner (upstream and downstream);
5. Hanger blade (upstream and downstream);
6. Hanger hub;
7. Sharp upstream cone;
8. **Rotor assembly:**
   - Rim type (see above discussion); or
   - Blade type (see above discussion);
9. Rotor bearings;
10. Shaft;
11. Smoother downstream cone;
12. **Top electrical enclosure comprising:**
    - Pickups;
    - Preamplifier.

The design of TFMs used in gas applications, such as fuel gas, gas injection, N_2 purge flow measurement, has some differences with respect to those used in liquid applications. Short discussions on TFM for gas applications have been presented in Section 2.1.6 below.

Pickups play an important role in turbine flow meters. As indicated earlier there are various kinds of pickup and as they are at the heart of the electrical output produced by the meter, they needs discussion in detail.



FLOW CONDITIONER SHOWN HERE THERE COULD BE ADDITIONAL HANGER BLADES ALSO IN ADDITION TO THIS.

FIGURE V/2.1.0-2 Velocity and pressure distribution—turbine meter.

2.1.3 PICKUP TYPES

To measure the flow there will be a number (one/two) of pickups mounted on the TFM body. Flow sensors generate voltage pulses, each voltage pulse representing a discrete volume (and frequency of output is a function of blade angle). The total number of pulses cumulated over a time period gives the total volume metered. Normally in

TFM volume flow per hour is measured. However, there are cases where turbine flow meters measure the flow rate in units of velocity, for example, length/s. There are mainly two types of turbine meter magnetic pickups, i.e., reluctance type and induction type pickups. Both types really rely on their magnetic property. There are a few other types, such as the Hall effect pick up, RF pickup, photoelectric pickup and even simple tachometer, mechanical or magnet drive can be deployed for the same purpose.

1. **Inductance type pickup (Fig. V/2.1.3-1B):** In its simplest form a permanent magnet is embedded in the rotor. Also, there is one pickup coil mounted on the meter body. Now, when the rotor rotates, the embedded magnet rotates past the pickup coil position, to generate a voltage pulse for every complete revolution of the rotor.
2. **Reluctance type (Fig. V/2.1.3-1A):** This is another kind where better resolutions are available. In this type a pickup coil is integrated

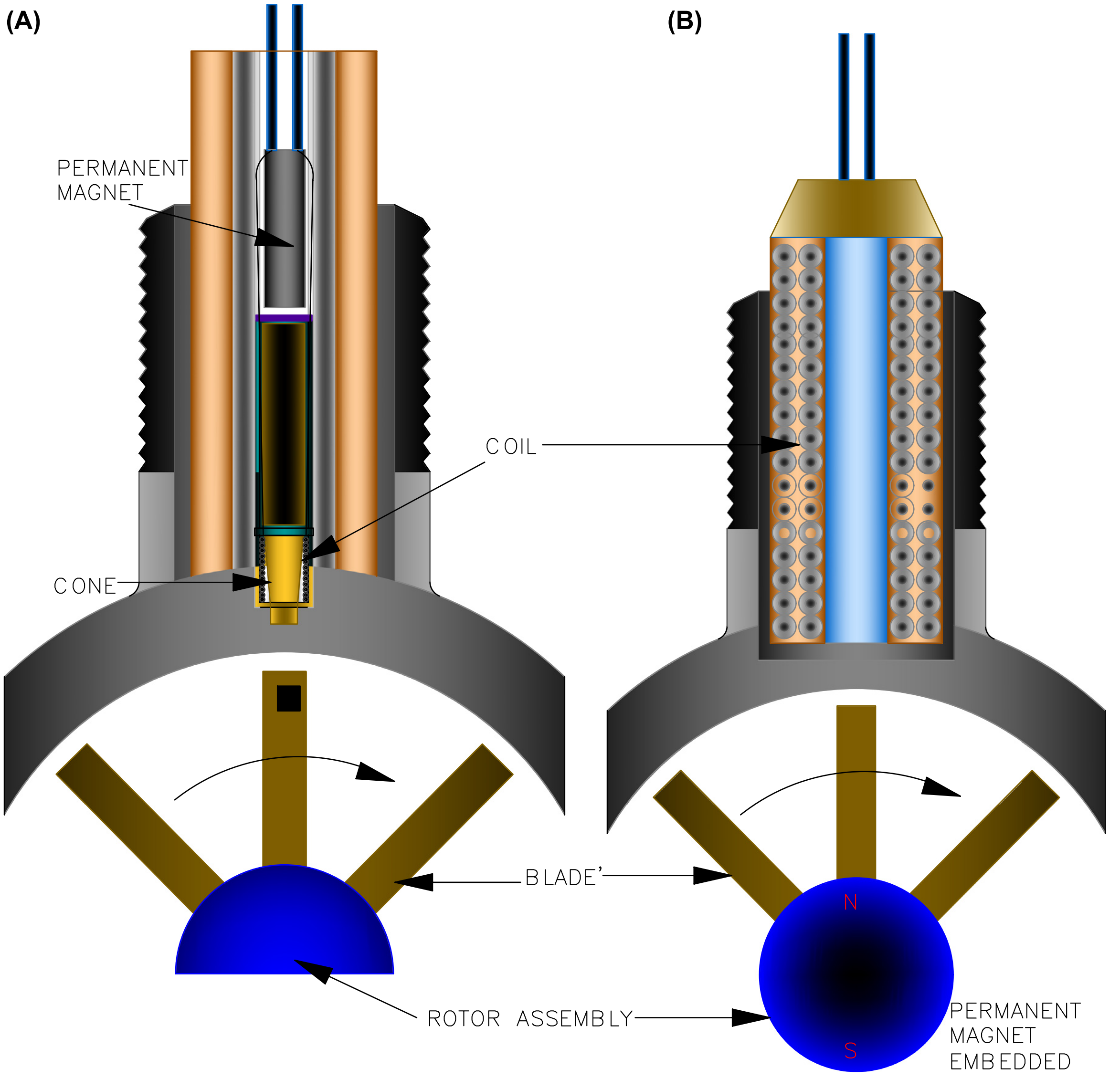


FIGURE V/2.1.3-1 Turbine flow meter pickups. (A) Reluctance pickup. (B) Inductance pickup. *Developed based on an idea from Transactions in Measurement Control, A Technical Reference Series, vol. 4, Omega, Flow and Level Measurement. http://www.omega.com/literature/transactions/transactions_vol_iv.pdf. Courtesy: oMEGA USA.*

with a permanent magnet (electromagnetic coil). Normally the field produced is concentrated with the help of a pointed cone. When rotor blades made from magnetically permeable ferrous material, the blade approaches the cone point, and its magnetic properties deflect the magnetic field to generate voltage in the coil. As the blade gets just past the cone point, the voltage decays, and the departing blade deflects the magnetic field in the opposite direction. To improve the resolution, especially at much lower angular velocities, small magnetic bars are inserted in a nonmagnetic rim that is fitted around the blades. This modification can improve the pulse resolution by as much as 10 times [5].

3. **RF sensor:** Radio frequency (RF) flow meter sensors are also used in turbine flow meters. These pickups are driven by an external radio frequency signal conditioner which is necessary to complete an oscillating circuit. The amplitude of the RF output of this circuit is *modulated* when a ferrous, 316 stainless steel (or aluminum) object passes by the pickup coil. Such change in modulation of the carrier frequency (RF carrier) is converted into a square wave pulse. In the case of TFMs these are frequently used for low-flow applications. For this type of pickup, meter recalibration may be required when the pickup is changed. This type of pickup is not only meant for TFM but could be used for other flow metering also.
4. **Hall effect sensor:** Hall effect sensors are also used for turbine flow meters, e.g., FTB373 of Omega or MT series of Trimec flow product. Brief details about the Hall effect sensor are given in Section 9.1.0 of Chapter IV, which may be referred to.
5. **Photoelectric sensor:** A photoelectric cell is also utilized in sensing the rotary motion of turbine blades for computing the volume flow through the turbine. The photoelectric sensor produces electrical pulses as the blades pass the sensor and/or obstruct the light path of the photo detector. The pulses are counted or totalized over a time period to sense the rotational velocity of the turbine.
6. **Pickup discussions:** Within magnetic pickups there are varieties as listed below.
   - *Low-drag magnetic pickup:* Used if extended range (say) 25:1 or better is necessary. These are especially suitable for low-sized meters.
   - *Modulated pickup:* These are used when pickup magnetic drags are eliminated, by modulating the signal with the carrier signal. These pickups offer good turndown ratio for the pickup, e.g., 100:1 [6].
   - *Quadrature pickup coils:* These are often used for bidirectional flow applications, and can even be used to compute differences of flow [6].

2.1.4 K FACTOR AND OTHER METER PERFORMANCE PARAMETERS

Meter K factor and linearity repeatability of the meter are interrelated terms for any turbine meter. Short discussions have been presented below to establish the relationships between these.

1. **K factor:** In these types of meters, where pickup output pulses are used to compute the volume flow, K factor is an important issue as it signifies the number of pulses per unit volume. Naturally this varies with the flow unit chosen. The issue has been addressed already in Chapter IV. With little modification of Eq. (V/2.1.0-1) one can write

$$q = 2\pi r \cdot A \cdot n \cdot \cot\beta \qquad \text{(V/2.1.4-1)}$$

i.e., $q \propto n$; where A is the pipe area, n = RPM.

This is in the case of an ideal situation when the meter would give the linear relationship between the meter output and the flow rate with constant K factor. Based on the meter size, the type K factor is determined for a turbine meter. The calibration of the meter is necessary to fix the specific K factor for the meter in question. However, when the K factor is plotted against flow rate, one will notice that it is not constant, but K factor changes with the flow rate. The driving torque of the fluid on the

rotor is influenced and balanced by the effects of viscosity, frictional effects, etc. Therefore, the shape of the K factor curve with flow rate is dependent on viscosity. Therefore, the K factor has a functional relationship with the flow rate and viscosity. Normally, the following relation is applied to take care of the viscosity effect.

$$\frac{n}{q} = K \cdot \frac{n}{\nu} \qquad \text{(V/2.1.4-2)}$$

where ν is the dynamic viscosity.

Normally the linear relationship of the K factor is confined to a flow range of about 8−10:1 as will be clear from Fig. V/2.1.4-1. In some cases there may be some extension.

2. **Linearity:** Linearity represent the deviation of maximum and minimum K factor from the average K factor. Naturally, in order to get the same one needs to plot the flow rate as shown in Fig. V/2.1.4-1. From the discussions in Subsection 2.1.4.1 this curve should be a linear flat one. In reality it can be seen that at a low flow rate there will be a drop off and also there will be a hump in the curve due to viscosity change. At the lower range of flow rate there will be a drop in linearity due to friction, viscosity, drag, etc. Another interesting feature is that there will be a hump due to viscosity in the calibration curve shown in Fig. V/2.1.4-1 at the low flow region and the hump flattens at lower viscosity. Better linearity is possible if this region is avoided. As shown for higher size meters better linearity is achievable. Currently it is possible to further linearize meter registration at the flow computer.
3. **Repeatability:** Repeatability has been defined in Chapter I, from where one can understand that this is the ability of a meter to indicate the same result or output reading each time for the same flow conditions. Turbine meters exhibit excellent repeatability of about 0.02% AR. Fig. V/2.1.4-1 shows repeatability of a meter in the right-hand side (RHS) diagram.
4. **Resolution:** This represents the smallest recognizable incremental flow. This is normally represented by a single pulse and in the case of a turbine flow meter this is excellent.
5. **Accuracy:** Normal accuracy of TFM available is in the range of 0.5%−0.15% AR (e.g., Bopp & Reuther high accuracy meter).
6. **Range: Turndown ratio:** Normally the range:turndown ratio represents the ratio of minimum flow range to maximum flow range

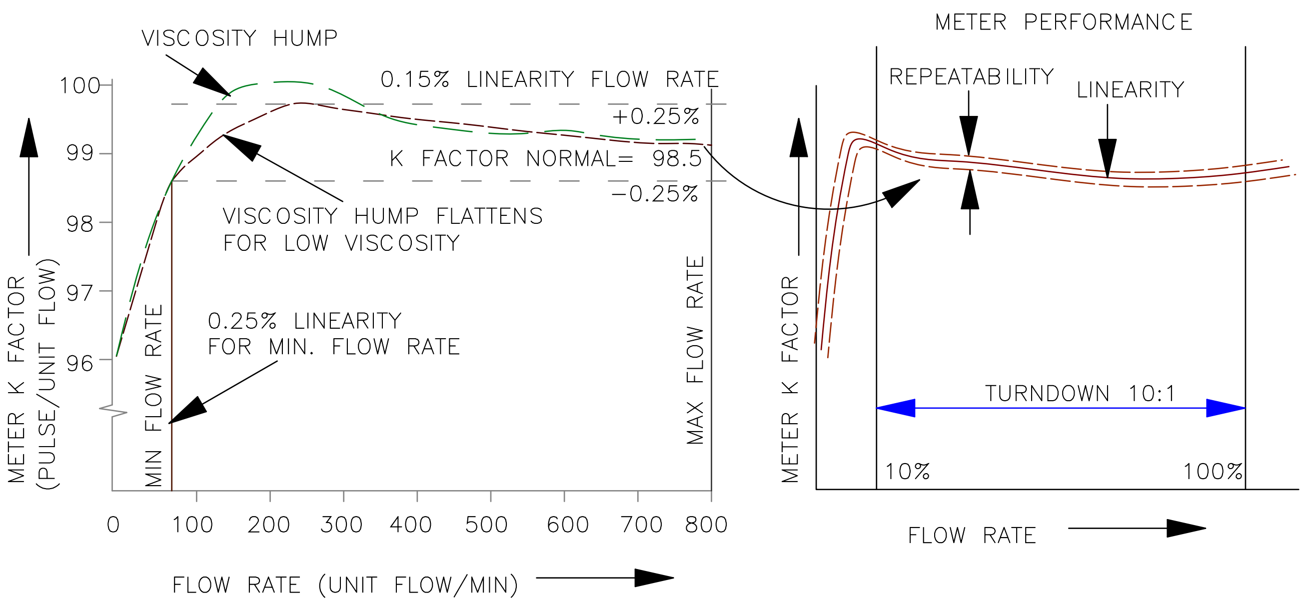


FIGURE V/2.1.4-1 K factor and meter performance.

and in the case of a turbine flow meter this is around 10:1. For better understanding, this has been depicted in the RHS diagram of Fig. V/2.1.4-1. However, one should note that 10:1 turndown is normal, and there are also extended turndown ratios. In all such cases modified pickups as described above are used.

With this it is better to look at the various features of the meter.

2.1.5 OPERATING PROCESS CONDITIONS

Turbine flow meters are capable of operating under extreme process conditions. The available meters are capable of operating at a wide range of pressures, temperatures, and viscosity conditions, within a specified accuracy.

1. **Pressure:** It could be applied for high-pressure applications. It could be applied for pressure up to 650 bar.
2. **Temperature:** It could be used at very low (<220°C) and high temperatures (>550°C).
3. **Flow range:** As discussed earlier, the normal turndown ratio is 10:1 extendable to a high turndown ratio. However, in various sizes the meters can cover quite a large flow range, e.g., from size DN10 to DN600 it can cover flow of >10,000 m^3/h.
4. **Viscosity:** It can support a wide range of viscosity in the medium viscosity category 1 to around 750 cP. However, the effect of viscosity is not easy to *predict* as it depends on size and type. Higher-sized meters are less affected by viscosity.
5. **Specific gravity/density:** It covers a wide range of specific gravity of fluids. Density does not have much effect of the meter sizing.
6. **Medium:** In general uses, turbine meters are more popular in liquid applications for high accuracy. However, it can be used for gas applications and is also used for custody transfer of natural gas. Normally the meter is meant to be used in clean fluids, but with a suitable strainer/filter, the meters can also be used for liquids with suspended solids.
7. **Pressure loss:** Pressure drop in the meter is a function of size, and medium. This is discussed separately later in this section.
8. **Backpressure:** In order to avoid cavitations it is necessary to maintain suitable backpressure.

2.1.6 BRIEF TECHNICAL DETAILS FOR GAS TURBINE FLOW METER

Here, brief technical details about gas turbine flow meters are provided to highlight the changes. The main discussions on gas turbine flow meters are covered in Section 2.8.2 of this chapter. Since TFMs in gas applications need to handle higher fluid velocities and lower driving torque, the meters are designed with larger hub diameters to give reduced pipe area. At the entrance of gas into the TFM, it is guided through an area between the meter internal diameter and deflector outlet diameter. Many gas TFMs have integral flow conditioners, to straighten the flow profile (and for gas acceleration). Since force increases with acceleration, to get greater rotor force, gas is accelerated by a deflector or flow conditioner. In gas TFMs, rotors are designed with more blades (25–30), properly positioned at a precise angle with flow stream. This ensures that the angular velocity of the rotor is directly proportional to the gas velocity. Rotors, and even the body, are made up of lightweight material such as aluminum. Gas TFMs may be calibrated with atmospheric air (or with natural gas) to traceable calibrated references. *When the measuring range gas turbine meter is determined under atmospheric conditions, then at higher operating pressures the measuring range of the turbine meters will increase since the required kinetic energy transfer to the turbine rotor occurs at lower velocities.* The measuring range equation may be used to estimate the minimum flow rate of the meter for various operating conditions [7].

$$q = q_{min} \times \sqrt{\frac{1.29 \times P_{atm}}{P \cdot \rho}} m^3/hr \quad (V/2.1.6\text{-}1)$$

where P = the meter operating pressure in Bar absolute; P_{atm} = 1.0132 BarA; ρ = density of

the gas at atmospheric pressure. Gas TFMs are flow meters available up to size 600 mm. Many gas TFMs are offered with the necessary lubrication systems. Further details on gas turbine flow meters can be found in Section 2.8.2 of this chapter.

2.2.0 Features and Applications of Turbine Flow Meters

In this section short discussions will be presented on the features and applications of TFMs.

2.2.1 FEATURES OF TURBINE FLOW METERS

A few salient features on turbine flow meters have been elaborated on below in terms of the advantages and disadvantages of turbine flow meter.

1. **Advantages:** The following are major advantages offered by TFMs.
   - Simple well understood technology;
   - Suitable for gases and liquids;
   - Both inline as well as insertion versions available;
   - Available with a number of accessories to support registering, batch controllers;
   - Acceptable for custody transfer applications;
   - High-resolution pulses make it possible to measure minute flow increments;
   - Available with built-in batteries for remote applications;
   - Relatively wide operational envelope;
   - Suitable for high-pressure applications;
   - *Good performance:* Accuracy up to 0.2% AR; repeatability: 0.05% AR;
   - Suitable for very low flow rates;
   - *Good turndown ratio:* normal 10:1; 20:1 extendable up to 100:1;
   - Wide temperature range;
   - Measurement of nonconductive liquids;
   - Wide range of material selections possible;
   - With suitable internal materials, pressure loss can be improved;
   - Suitable for very low flow rates;
   - Applicable for both liquid and gas;
   - Moderate cost;
   - Lightweight TFMs are also available;
   - Wide design of electrical enclosure for safety applications and harsh environment applications;
   - Easy installation and operation for meter and pickups;
   - Suitable electronics for easy integration with modern systems.
2. **Disadvantages:** The following are the major limitations of TFMs.
   - High wear due to moving parts;
   - Applicable for clean fluids;
   - Problems due to cavitations;
   - Subject to erosion and damage;
   - Accuracy is affected by bearing degradation;
   - Maintenance will be high, especially for dirty fluid applications;
   - Installation must be done carefully to avoid errors;
   - Not suitable for high-viscosity fluid;
   - Viscosity must be known;
   - K factor is dependent on viscosity;
   - Errors caused by viscosity changes;
   - Require frequent calibration checks;
   - Not suitable for highly viscous fluids;
   - Higher requirement of straight length (U:10D/D:5D);
   - Not suitable for fluids with swirling motion;
   - Pipe system must not vibrate;
   - Sizing and specifications critical for applications;
   - Requires additional support for large meters.

2.2.2 APPLICATION OF TFMs

In industrial as well as sanitary applications, turbine flow meters are used. Some major application areas of turbine flow meters include but are not limited to the following:

1. Turbine flow meters measure the velocity as well as flow of liquids, gases, and vapors in pipes, such as cryogenic liquids, hydrocarbons,

chemicals, water (municipal water distribution), air, and industrial gases.
2. For sanitary applications TFMs also have uses.
3. Apart from petroleum applications, usages also include the food and beverage industries, as well as in power plants, waste water services, aerospace, metals and mining, pulp and paper, pharmaceutical, and other chemical industries.
4. TFMs are frequently applied for batch and blending applications.
5. For loading and unloading operation of refined products TFMs are often used.
6. High-accuracy TFMs are available for custody transfer of hydrocarbons and natural gas.
7. Often these flow meters along with associated accessories are used to obtain density-corrected flow calculations and applications.
8. TFMs are used with liquids without lubricating properties, so one must be careful about early bearing failure. Also, in high-viscosity applications early bearing failure can occur, therefore, necessary precautions are important.
9. Especially designed TFMs with greased bearings for special applications, such as natural gas, may be vulnerable at high temperatures.
10. Gas TFMs are used for fuel measurements, N2 injection, and air compressors.

2.3.0 Design Aspects of Turbine Flow Meters

While discussing turbine meter design, it is necessary that the meter should have a rugged rotor body. However, depending on the meter size, a rugged body may also invite an asymmetrical transient response characteristic [3]. Bearing design in turbine meters is *very* important because a good bearing would help in minimizing the mechanical friction. Apart from the design, during *operational* conditions also, it is necessary to monitor bearings so that they are not damaged or dried out, and it is necessary for them to be properly maintained and oiled, to ensure no meter errors or problems arise due to friction. Based on the rotor, bearing, and pickup design the turbine flow metering technology varies greatly. Therefore it is very much pertinent to put an emphasis on meter design selection and sizes. During operation, the manufacturer's recommendations cannot be overstated.

2.3.1 METER HOUSING

The meter housing subassembly can be constructed and developed from a flanged pipe spool in a wide range of sizes from DN 10 to DN 600. Process connections can be screwed (NPT/BSP), sanitary clamp, and most popularly flange connections of different ratings as per international standard (ANSI/DIN), Since flanges does not come into contact with fluid, material selection for flanges mainly comes down to pressure and temperature ratings and not fluid considerations. The materials used for the housing are normally nonmagnetic, so that being in the near vicinity of the pickup it does not affect the pickup based on magnetic sensing. A deflector ring is used with rimmed rotors to prevent the flow stream from impacting on the rotor rim [8]. Depending on the types of pickup chosen, a single or more pickups are mounted on the housing. For a quadrature pickup discussed earlier these are at 90°.

2.3.2 ROTOR ASSEMBLY AND SOME OTHER METER INTERNALS

A rotor assembly (rotor along with blades) is the moving/rotating part in a turbine meter. Rotor assembly, in its simplest form, consists of a series of blades (in rim or without rim) that are fixed to a hub at a specific angle.

1. **Blade angle:** The sharper the blade angle, the higher will be the frequency output. If a larger angle is chosen there may be excessive end thrust. In contrast, a lower angle will cause lower angular velocity and lower repeatability. Therefore, normally the blade angle is kept between 20 and 40 degrees to the flow [3]. The rotor assembly is mounted on a shaft that is

suspended in the flow stream by bearing(s) or stator(s). The rotor is free to rotate on bearings.

2. **Blades:** The number of blades in a hub depends on the design—usually 6−16 blades are fixed on the hub. There are two options for rotor assembly with regards to blades: rotors may be rimless (open-bladed) or rimmed.
3. **Rimless rotors:** Open-bladed (rimless) rotors are most commonly used for lighter fluids, having a specific gravity near 0.7 and viscosity less than 10 cP and/or on smaller meters with line sizes <150 mm. Usually these rimless rotors are made up of paramagnetic material, e.g., steel, etc. for easy detection, e.g., by a reluctance type pickup. In this case, pulses per revolution are limited by the number of blades. However, for certain sizes, both bladed (rimless) as well as rimmed rotors are possible. In this connection Table V/2.4.2-2 may be referenced.
4. **Rimmed rotors:** For measuring more viscous liquids and/or in larger size >150 mm meters, rimmed rotors are used for better rigidity. In the case of bladed rotors, pulses per revolution are limited by the number of blades. In rimmed rotors the number of pulses per revolution corresponds to the number of buttons or slots in the rim. Hence, in this case, better resolution is expected (see Table V/2.4.2-2). In order to prevent the flow stream from impacting on the rotor rim a deflector ring is used with rimmed rotors.
5. **Low mass design:** A low mass design of rotor has an inherent advantage of better dynamic response and such design is helpful for pulsating flows. The hydrodynamic positioning of the low mass rotor provides wider rangeability and longer bearing life than that of conventional turbine flow meters [6].
6. **Cones:** There are two cones in turbine flow meters. The functions of these have been discussed in Section 2.1.2 in this chapter. Deflector cones eliminate downstream thrust on the rotor and allow for hydrodynamic positioning of the rotor between deflector cones [6].
7. **Hanger:** There may be a single hanger or two hangers, one each upstream and downstream of the rotor. Hanger blades are fixed on a hanger hub. These integral flow-straightening tubes minimize the effects of flow turbulence. In some meters integral flow conditioners are used in addition to hangers.

2.3.3 TURBINE FLOW METER BEARINGS

There are a variety of bearing types and materials used in turbine flow meters. A major issue is that in order to reduce frictional loss and avoid meter failure it is essential that bearings are well maintained and properly monitored. In turbine flow meters, often the flowing fluid provides the bearing lubrication. However, it is necessary to keep the bearing well polished, especially for nonlubricating fluids, to avoid frictional loss. There are two types of bearing design styles available. One is a cantilever design supporting only the upstream side and another type of bearing that supports the rotor at both ends. The cantilever design is well suited for smaller and lightweight meters. Obviously, large rotors will require support at both ends. Each of the bearing types has its own applications. The bearing design influences meter performance parameters, including accuracy and repeatability. Also, for long service of the meter it is necessary that the bearing design and selection are good and proper. One may note that the higher the speed of the bearing, the lower will be its service life. A short discussion is presented below that may be helpful for selection.

1. **Material:** Tungsten carbide, Teflon, and carbon graphite composites are common materials used as bearing materials. When selecting among several chemically compatible bearings, the ball bearing design offers the highest accuracy and generally will have the widest usable range [6]. Tungsten carbide is famous for its durability and so it is the general choice for a variety of liquid and gas applications. On account of their inertness, Teflon and carbon graphite composite bearings are chosen for

many corrosive fluids. Ceramic journal or sleeve bearings are used for nonlubricating fluids or for high-temperature applications. Stainless steel is mostly used for the ball bearings.

2. **Journal/sleeve bearings:** Hard-surfaced journal bearings and hard-surfaced washers are popular in petroleum applications. Tungsten carbide is extremely hard wearing. Therefore, tungsten carbide journal bearings are mostly used in normal processes or pipeline applications requiring continuous operations. These are helpful in getting sufficient longevity and to minimize maintenance intervals. These are also used for crude oil and other dirty fluids applications.
3. **Ball bearings:** Ball bearings are very suitable for low flow rates and on clean products for better performance, such as accuracy. Ball bearings are also used for intermittent duties on light, clean fluids, i.e., tank truck terminals, and loading/unloading operations. In this design, two ball races and a short axle are used for meter design. Ball races are fitted on the rotor hub to economize space. In these installations, liquids are typically light, refined products.

2.3.4 ELECTRONIC UNIT

Like PD meters, turbine flow meters also have associated electronic units that play a major role from an application point of view. Starting from the pickup signal, there can be a preamplifier, flow conditioner, computation, etc. All these are kept in an enclosure with a suitable IP rating (IP 65 common, IP 67 possible). One of the major functions of this electronics is to process the signals from the pickup(s). In the case of applications where failure cannot be tolerated, usually dual or four pickups are used. The pulse transmission signal fidelity test is extremely important. These pickups may be in quadrature or a pairs of pickups in quadrature for four pickup sets. Apart from this, another important function of an electronic unit is the display unit and control functions. The displays in most turbine flow meters are rate flow indications as well as totalized flow indications. This electronic unit also performs the following functions:

1. **Rate flow:** Signal conditioning functions to interpret pulse signal to convert to engineering unit for rate display;
2. **Totalized flow:** Totalizing function to give total flow display in desired unit;
3. **Preset batch function:** This is a dispensing function to carry out countdown to zero to send a signal for closure of a valve. Often, to avoid hydraulic shock, the preset batch unit can be fitted with an advance warning contact, or it can incorporate a ramp function [9];
4. **Automatic temperature compensation:** Many applications require temperature compensation of fluid flow, especially for gas flow applications. Therefore, the electronics need to compute the compensated flow output;
5. **Batch and blending control:** Turbine flow meters are often used for batch and blending operations, so necessary functions need to be incorporated in the associated electronics.

2.3.5 ENVIRONMENTAL CONDITIONS

Turbine flow meters are available to suit harsh environmental conditions. It is possible to operate the meters in environmental temperature range −20 to 70°C (storage) and −10 to 70°C (operational) with relative humidity up to 90%. Climate category. As per IEC654-1 are also available.

2.4.0 Material Selection, Sizing, and Flow Range

Turbine meter selection and sizing are important to get proper functioning and performance of the meter. For meter sizing and selection, when the following steps are followed then one can expect to get the optimum selection of meter for a particular application.

- Choosing meter size based on flow range and process conditions;
- Selection of material for various meter parts based on process conditions;
- Selection of bearing based on process as well as duty cycle;
- Choice of pickups based on size and application;
- Calibration requirement and facilities.

Of these criteria, some have already been discussed, in this section discussions will be concentrated on the top two issues discussed above. It is needless to say that selection of materials for various parts is extremely important, especially for critical process fluids, i.e., for corrosive fluids, dirty fluids, etc.

2.4.1 MATERIAL SELECTION

Turbine flow meters are available in a wide range of materials—standard materials as well as special materials for particular services. Also, based on the application, there could be a number of construction options available for the designer to select regarding flow range, corrosion resistivity etc. Such construction options have been covered in the above discussions. As indicated earlier, the housing is made of nonmagnetic materials, while the rotor is made of magnetic or magnetized material. Brief guidelines have been enumerated below regarding the available materials.

1. **Rotor body and support:** 316 SS 17.4 pH SS, nickel 200 and 430 SS, brass, aluminum (gas-TFM);
2. **Insertion meter:** Nickel-plated brass;
3. **Rotor materials:** 17.4 PH SS, nickel 200 and 430 SS, PVDF, (SS304 Blade), aluminum (gas TFM);
4. **Shaft:** Tungsten carbide, SS 304, aluminum;
5. **Bearing:** SS316, 440Css, tungsten carbide, graphite, ceramic, etc.;
6. **Sleeve:** 304SS;
7. **Diffuser:** SS316, aluminum (gas);
8. **Cone:** SS 304/316;
9. **Special materials for meter:** Teflon, 4130 steel, Monel, other grades of stainless steel, Hastalloy, titanium, tantalum;
10. **Flow conditioning:** SS, aluminum, Delrin.

2.4.2 METER SIZING AND FLOW RANGE

The turbine flow meter is a velocity-sensing device and flow is measured by $q = A \cdot v$ where A is the area and v is the velocity. Thus there is a linear relationship between velocity and flow. Therefore, one needs to size the meter meaning to find A (area, i.e., meter diameter). Any flow meter has specific maximum and minimum linear flow-measuring capability and often the difference between them is referred to as the flow meter range, which is the major criterion for meter sizing. However, a number of other process conditions affect the flow capability of the meter. Therefore it is essential to address these conditions.

1. **Basic sizing criterion:** In turbine flow meters there is a linear relationship of flow with velocity (unlike a DP type flow meter where normally the maximum flow is chosen at 90% of the meter range). For meter sizing purposes it is recommended that the maximum flow rate of the application should fall at approximately 70%–75% of the maximum flow rate of the meter, still keeping approximately 25% spare capacity to allow for future expansion. Such selection would give good flow rangeability of about 10:1 for most manufacturers. The text now concentrates on various affecting factors.
2. **Viscosity effect:** The above standard rule may not be applicable for high-viscosity applications. Smaller flow meters are more affected by viscosity than larger meters. If one recalls the discussions on linearity in Subsection 2.1.4.2 one would notice humps are created at the lower end of the range. Keeping these two issues in mind one would size one's meter a size smaller, so that the maximum flow rate

occurs at a high-flow region corresponding to that size. As the viscosity effect is greater at a lower range, one has to raise the minimum range. This increase in flow rate is determined by sizing ratio given by: *sizing ratio* = liquid viscosity in cSt/nominal line size in inches. So, for viscosity of 12 cST for a nominal size of 150 mm sizing ratio = 12/(150/25) = 2. There are charts available for sizing ratio to minimum flow range as percent of nominal maximum flow range, presented as Table V/2.4.2-1 below.

For better performance, approximately 9 m/s velocity is preferred when normal liquid velocity in the pipe is around 2−3 m/s. Empirical concept of meter size = pipe size is limited for range ratio limited to 2:1 or 3:1 only [9]. In cases of reduced meter sizes a cone type reducer allowing the required straight length is used. However, for very high viscosity instead of turbine flow meters, PD meters may be considered.

3. **Pressure loss:** Pressure loss and flow profile are discussed in the next section. However, for the selection process, pressure loss affects the selection in another way, meaning that the maximum application flow rate should be approximately 75% of the meter range. However, pressure loss reduces with the square of flow rate. This means that if the meter is operating at 50%, the pressure loss will be reduced to 25% of that at maximum flow rate. From the above discussions it transpires that if the meter is operated at the lower range the pressure loss will be less (but viscosity effect will be more!). Pressure loss is important for cavitations and back pressure.
4. **Cavitations and back pressure:** Velocity and pressure distribution inside a turbine flow meter are depicted in Fig. V/2.1.0-2. It is essential to increase back pressure to prevent liquid cavitations in the rotor region. It is better to follow API recommendations; if "BP" represents minimum back pressure at the meter, "VP" is the vapor pressure of the liquid, then as per API recommendations the required back pressure is given by:

$$BP = 2 \times \Delta P + 1.25 \times VP \qquad (V/2.4.2\text{-}1)$$

Here ΔP represents the pressure drop. For a better understanding, Fig. V/2.4.2-1 may be referenced. Therefore, due considerations shall be given to the same while sizing the meter. This means it is necessary to select a meter

TABLE V/2.4.2-1 Sizing Ratio—TFM

Sizing Ratio	Minimum Flow Range as % Normal Max Flow Range
1.5	20
2	25
2.5	30
3	35
4	40
5	45
6	50
7	55
8	60

This chart has been taken from Daniel Liquid flow meter Daniel™ Liquid Turbine Flow Meters, Technical Guide, Daniel –Emerson, April 2015. http://www2.emersonprocess.com/siteadmincenter/PM%20Daniel%20Documents/Turbine-Meter-Tech-Guide.pdf. Courtesy: Daniel: Emerson.

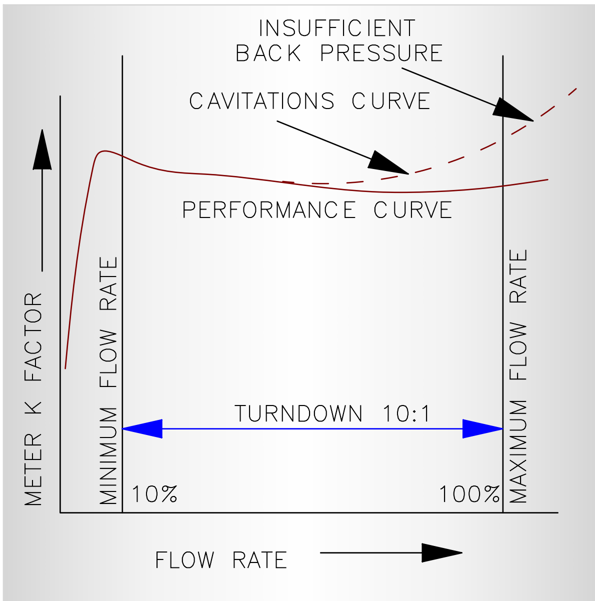


FIGURE V/2.4.2-1 TFM performance at cavitation.

TABLE V/2.4.2-2 Typical Flow Range of Turbine Flow Meter

Meter Size[a]	Min Flow[b]	Max Flow[b]	Pulse Count		Remarks
			Bladed	Rim	
15	100*	1100*	4000*		*Flow in L/h and count pulse/L
20	220*	2200*	1700*		
25	1.6	16*	132,086		*Extended range: 18
50	6.8	68*	34,342		*Extended range: 78
100	29.4	294	6287	18,492	*Extended range: 338
150	66.8	668	1532	6604	*Extended range: 768
250	191	1908		3461	*Extended range: 2194
300	286	2862		1268	*Extended range: 3291
400	445	4452		634	*Extended range: 5120
500	763	7631		634	*Extended range: 8776
600	954	9539		634	*Extended range: 10970

[a,b]are meter size and flow range respectively as explained in Subsection 2.4.2.5.
Courtesy: Trimec flow product (for DN 15 and 20) and Daniel liquid flow meter (for DN 25 to 600).

range so that at the application maximum flow the pressure drop meets Eq. (V/2.4.2-1). In other words, it is necessary to ensure that the line pressure is sufficient.

5. **Flow range:** Some typical flow ranges from some reputed manufacturers are presented in Table V/2.4.2-2. Unless specifically stated otherwise, the following are the units used. (a) Meter size in (mm) DN; (b) flow in m^3/h; pulse count: DN15 and 20: pulse/lit; rest in pulse/m^3: Conversion 1 In. = 25 mm; 1 m^3/h = 16.66 LPM = 264.17 gallons/h.

2.5.0 Flow Profile Straight Length Requirements and Pressure Loss Estimation

Variations in velocity profile and/or fluid swirl are common causes of measurement errors. The effect of profile distortion on flow measurement has been discussed at length in Chapter I, so is not discussed again here. Profile distortions causing measurement errors are normally circumvented by the use of a straight pipe length. Long straight upstream piping ensures that all of the energy of the disturbance is dissipated or settled down before the flow reaches the turbine meter. In this section such profile distortions, straight length requirement, and pressure loss pertinent to TFM are discussed briefly.

2.5.1 FLOW PROFILE DISTORTION

When one recaps the discussions presented in Chapter I, one can recall that velocity-sensing turbine meter accuracy largely depends on the defined flow profile. Therefore it is essential that the location of the meter shall be such that enough straight length is available both upstream and downstream of the meter so that the energy of the disturbance is dissipated before the flow reaches the meter, i.e., to maintain the defined flow profile mentioned. As mentioned above, a typical installation may call for 10D to 15D (D): pipe inner diameter [ID] of straight pipe upstream and five pipe diameters (D) of straight pipes downstream of a turbine meter. In reality it is often not possible to get enough space and long pipe runs. Therefore, to

circumvent this situation, auxiliary equipment such as flow-straightening vanes or flow-conditioning plates (detailed in Chapter XI) are used. The side effect of these auxiliary devices is higher pressure loss in the system—and hence loss of energy. The introduction of costly surge-filtering devices is found in many cases to minimize flow measurement error.

2.5.2 STRAIGHT LENGTH REQUIREMENT AND FLOW CONDITIONERS

As indicated earlier, the standard straight length of pipe required upstream and downstream for a turbine flow meter is 10D and 5D, respectively. However, in certain insertion type meters, even up to 2D upstream straight length requirement recommendations have been noticed (e.g., Series F-1100 of Onicon TFM). However, these are general values. Based on the type of obstruction it may vary, examples are given here:

- **Concentric reducer:** 15D;
- **Sweeping TEE or elbow:** 25D;
- **Partially opened valve/two elbows at 90°:** 50D;
- **Gate/ball valves:** 15D.

In reality it may not be possible to meet these straight length requirements. As indicated in Section 2.5.1, flow conditioners and straighteners are used. In this regard recommendations standard API Chapter 5.3 as shown in Fig. V/2.5.2-1 may be followed. New flow conditioners have been recently introduced which can further reduce flow distortion over a wider range of operating conditions [8]. Flow conditioners discussed in Chapter XI, so reader may refer to Chapter XI, may be referenced.

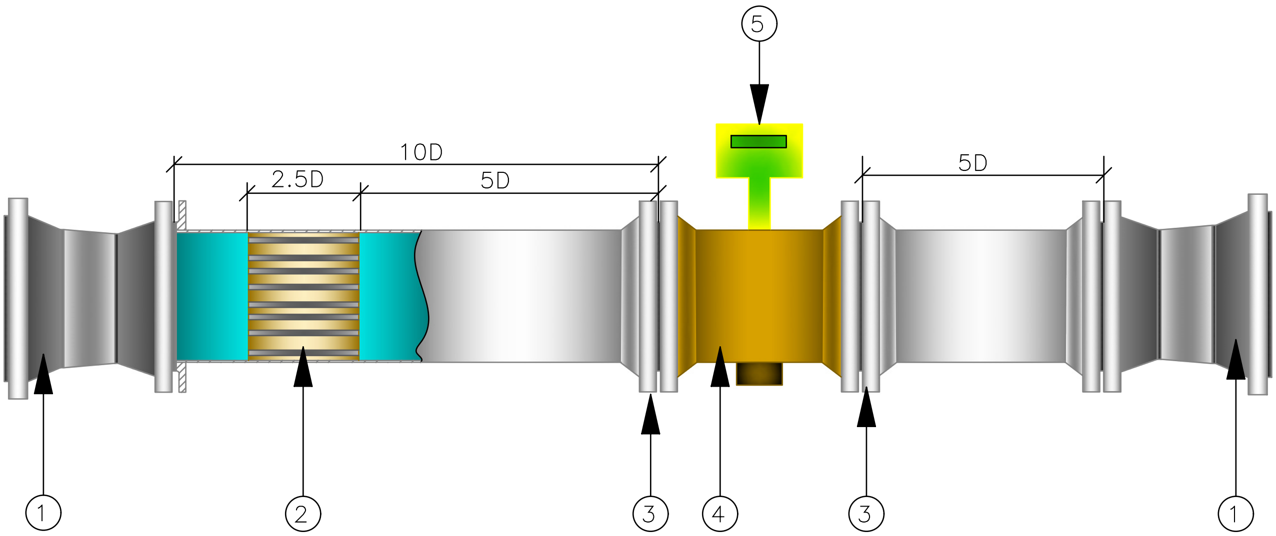


FIGURE V/2.5.2-1 Straight pipe work for TFM. (1) Concentric cone reducer effective for high-viscosity service. (2) Flow conditioner (straightener/vane or modern inserted conditioner). (3) Turbine flow meter and flow conditioner connections (flanged shown here). (4) Turbine flow meter of internal diameter "d." (5) Electronic unit/display unit for turbine meter. Note: (1) Not drawn to scale. (2) For gas application, there will be meter downstream temperature tapping and upstream side pressure tapping (not shown) for measuring compensated flow. *Developed based on idea from F. Frenzel, H. Grothey, C. Habersetzer, M. Hiatt, W. Hogrefe, M. Kirchner, G. Lütkepohl, W. Marchewka, U. Mecke, M. Ohm, F. Otto, K.-H. Rackebrandt, D. Sievert, A. Thöne, H.-J. Wegener, F. Buhl, C. Koch, L. Deppe, E. Horlebein, A. Schüssler, U. Pohl, B. Jung, H. Lawrence, F. Lohrengel, G. Rasche, S. Pagano, A. Kaiser, T. Mutongo, 2011. Industrial Flow Measurement Basics and Practice, ABB Automation Products GmbH. http://nfogm.no/wp-content/uploads/2015/04/Industrial-Flow-Measurement_Basics-and-Practice.pdf.*

2.5.3 PRESSURE DROP ESTIMATION

Turbine flow meters are intrusive flow measurement devices, and so it is extremely important that due consideration is given to pressure drops at the maximum flow rate while designing a system. It is again reiterated that TFMs should be used for low- to medium-viscosity fluids. Normally pressure drops at the rated flow are specified by manufacturers. However, in most of cases these values are based on water at 16°C. In the low- to medium-viscosity range, precise pressure loss through the meter can be calculated by:

$$\Delta p = (PD_w) \cdot \mu^{1/4} \times SG^{3/4} \text{ or } (PD_w) \cdot v^{1/4} \times SG \,[\text{as } \mu = (v) \times (SG)] \quad \text{(V/2.5.0-1)}$$

where Δp = precise pressure drop; PD_w = pressure drop for water at rated flow; μ = absolute viscosity in centipoises; v = kinematic viscosity in centistokes; and SG = specific gravity.

As we have seen in Subsection 2.4.2.4 this has a direct bearing on cavitations in the meter. The effect of pressure loss in meter sizing has been detailed in Subsection 2.4.2.3. Hence necessary measures should be considered while sizing the meter.

With these points borne in mind, the next section discusses how to select the correct turbine flow meter.

2.6.0 Specification of Turbine Flow Meter

A short specification of a turbine flow meter has been presented in Table V/2.6.0-1. It is worth noting that line size and meter flow range are very important parameters and these are to be decided at the early stage based on guidelines discussed in Section 2.4.2. These parameters should be a part of the specification not shown in the Table V/2.6.0-1. In order to put extra importance for the same treated separately here instead of including in the table. In this connection, the specification given in Section 2.8.0 should be referenced.

Having specified the meter it is then better to look into the installation and calibration of the same.

TABLE V/2.6.0-1 Turbine Flow Meter Specification

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Liquid/gas (say)*		* Also to specify fluid. ***Liquid and gas TFM are separate***
2	Design pressure	650 bar (max)		
3	Design temperature	(−)220−550°C		
4	Viscosity	Low medium up to 750 cP(max)		
5	Registration	US/imperial gallon, liter		To specify
6	Pick up type	Magnetic/mechanical/hall effect/photoelectric		
7	Output	Pulse (variety of frequency range, e.g., 0−5 kHz)/ 4−20 mADC smart version with HART protocol available		
8	Output function	Mechanical totalizing/batch control/blending and batching, electromechanical totalizing, electronic totalizer, remote transmission, pressure temperature compensation		

Continued

TABLE V/2.6.0-1 Turbine Flow Meter Specification—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
9	Materials of construction	Refer to Section 2.4.1 and Subsection 2.3.3.1		
10	Electronics unit	ABS, epoxy encapsulated		
Connection and Mounting Details				
11	Process	½″ to 2 ½″ NPT, or flange Din/ANSI standard pressure rating matching application		
12	Electrical	½″ NPT/ET or manufacturer standard		
13	Mounting	Horizontal or vertical		
14	Temperature and pressure compensation	Where required to be provided, normally downstream side tapping (especially for temperature tapping)		
Performance and Other Details				
15	Accuracy	±0.15 AR−0.5% FSD		
16	Repeatability	<±0.02% FSD		
17	Certification	Necessary certification from appropriate authority for hazardous application		
18	Application	Water/oil petroleum products		
19	Accessories	Rate flow and totalizing indicator, transmitter, batch controller, blending controller, strainer, etc.		
20	Preamplifier	Converts sinusoidal signal to square pulse at variable frequencies		
21	Special feature	If any to specify requirement		

The maximum available values for different meters given here may differ from those of any particular model—the designer should specify data pertinent to the application. *Line size and flow range should be a part of the specification though here treated separately.*

2.7.0 Installation and Calibration

ISA−RP31.1 provides guidelines for turbine flow meter installations and calibration. As a general principle the same needs to be consulted and followed. However, manufacturers' recommendations, as given in the form of a manual, provide specific guidelines for the meter in the application (when selected correctly). In this section installation and calibration are discussed, respectively.

2.7.1 INSTALLATION DISCUSSIONS

1. **ISA Guideline:** According to ISA−RP31.1, the following are major issues that should be addressed for meter installation.
   - *Environmental considerations:* Environmental conditions affect TFM operation, therefore, it is better to choose a weatherproof enclosure for electrical components.

- *Piping configuration:* Piping work, as already discussed, should be followed to avoid errors due to distortion of flow profile.
- *Flow direction:* During installation it is necessary to follow the flow direction.
- *Flow straightener/conditioner:* Flow conditioners should be used as recommended.
- *Flow attitude:* Turbine flow meters should be installed in the same position as they were calibrated, if mounted in other ways necessary corrections need to be incorporated.
- *Filtration:* In case of dirty fluid and fluids with suspended solids, a suitable filter should be deployed. ISA RP31.1 may be referenced for further details.
- *Cabling:* Use of suitable shielded cables of required conductors as recommended by manufacturer should be followed.
- *Proper earthlings:* The shield should be properly earthed in one point.
- *Excess torque for transducer:* While installing the meter it is necessary to ensure that there is no excess toque applied.

  For further details the latest version of ISA–RP31.1 may be referenced.

2. **Other pertinent mechanical issues:** Here a few other guidelines for installation are discussed.
   - *Flushing:* Prior to installation it is necessary to purge and flush the pipe to remove oils, dirt, welding remains, and for cleaning purposes. During such operation it is necessary to replace the meter with a suitable spool piece.
   - *Mounting:* For mounting it is essential to follow the direction of flow, mounting style, flow conditioner, etc. already stated above.
   - *Compensation:* For temperature and pressure compensation (as applicable) necessary tapping points should be placed in the outlet section of the meter housing—distance: 3 × nominal width for the pressure and 5 × nominal width for temperature [10]. Also, the installation specification section of the AGA Report No. 7 [9] provides good guidelines for the placement of the temperature well and pressure tap on a turbine meter.
   - *Strainer:* For fluids with solids, etc., like PD meters, a suitable mesh strainer is recommended to avoid mechanical damage to the turbine meter and to ensure a longer meter life. The mesh size of strainers is a function of the meter size. Typical sizes and associated mesh details have been elaborated in Table V/2.7.1-1.

TABLE V/2.7.1-1 Strainer Details

Meter Size (mmNB)	Mesh No	US Sieve No	Opening Size in mm (Inch)
<15	115	120	0.125 (0.0049″)
15–40	42	45	0.354 (0.0139″)
>40	16	18	1.0 (0.0394″)

3. **Other pertinent electrical issues:** Cable types to be used are found either as accessories with the meter and/or are given in the recommendations from the manufacturer (e.g., Beldon 8422 for Hoffer Turbine Flow meter). Guidelines for such cabling and earthings have been covered above. Proper care however is necessary to eliminate noise in the system by the use of a suitable signal conditioner/filter circuit or preamplifier, etc. and these should not be placed too far from the meter. One needs to follow the recommendations from the manufacturer. Proper interface of flow meter output with the electronic unit is vital. In the case of smart devices and analog output devices wiring, load resistance is an important issue to be properly addressed as per the manufacturer's recommendations.

2.7.2 CALIBRATION DISCUSSIONS

According to ISA RP 31.1, the following methods are suitable for the calibration of turbine flow meters:

- Gravimetric (direct or indirect);
- Volumetric;
- Comparison.

Each of these methods has advantages and disadvantages depending upon the liquid being metered and the type of operation. The gravimetric methods require that the density of the liquid be determined accurately to provide a basis for converting mass to volume. The effect of the gas added to the "weigh" tank in closed gravimetric calibrators must also be considered. There is another way of classifying calibrators either as the open-type (for use with low vapor pressure liquids) or the closed-type in which a back pressure greater than atmospheric is maintained to prevent liquid loss from the measuring vessel by evaporation. Other types include static, dynamic, and start-finish methods.

Comparison is another method of calibration. For field calibration and testing, this method is used. For this minimum equipment is required and it is well suited for routine calibration of turbine flow meters. As for comparison, a secondary standard is used, and the probability of total uncertainty may increase. In operation, a reference turbine flow meter is installed in series with the flow meter to be calibrated and the proper steps are taken to reduce pulsation and swirl at the inlet of both units [11].

These have been discussed in Section 2.4.0 in Chapter II. For details, ISA RP 31.1 and Chapter II of this book may be referenced.

For data presentation ISA RP31.1 provides a standard format which may be used for calibration test results.

With this the discussions on inline turbine flow meters comes to an end. Now short discussions shall be presented on insertion turbine flow meters.

2.8.0 Other Turbine Type Flow Meters

There have been a number of developments in the area of turbine flow meters. As a result, a few other types of turbine flow meters than those described above have been launched. In this section short discussions on these are provided. These include: insertion type turbine flow meters, gas turbine flow meters, dual rotor turbine flow meters, and twin turbine flow meters. There are also twin turbine mass flow meters that are discussed in Chapter VI.

2.8.1 INSERTION TYPE TURBINE FLOW METER

In contrast to inline TFMs, where the total velocity profile of the pipe is taken into consideration for measurement, the insertion flow meter is a local single-point velocity sensing type. In view of this, the insertion TFM is less accurate than its inline meter counterpart. So, in insertion TFM, velocity profile can either be established by a series of measurements across the pipeline and establishing the fluid velocity profile, or by taking the measurement at the optimal (compromise) insertion depth near half of the pipe internal diameter from the surface.

Insertion type turbine flow meters are mainly used in large-diameter pipelines where the cost of inline meters would be prohibitive. These are used for conductive, low-viscosity liquids in full, pressurized pipes. For this reason they are provided with suitable valve arrangements so that installation and removal of the meter from the pipeline without interruption to flow is possible. In such applications these meters are an economic solution to achieving high-accuracy flow metering. Heating ventilation and air conditioning (HVAC) is a typical area of application. Typical insertion type turbine flow meter General arrangement (GA) and internals have been depicted in Fig. V/2.8.0-1.

There are special design insertion type TFMs that offer all the accuracy of measurement and taking average speed of rotation of two turbines with opposite helices, minimizing the effects of swirl, the most common flow distortion caused by pipe bends and elbows, e.g., the F-1200 Series meter of Onicon [12]. Insertion type flow meters are available for different pipe sizes from 40 to 1800 mmNB pipes. We now explore some associated data pertinent to these types of meter. Data given here pertain to maximum possible values in various models.

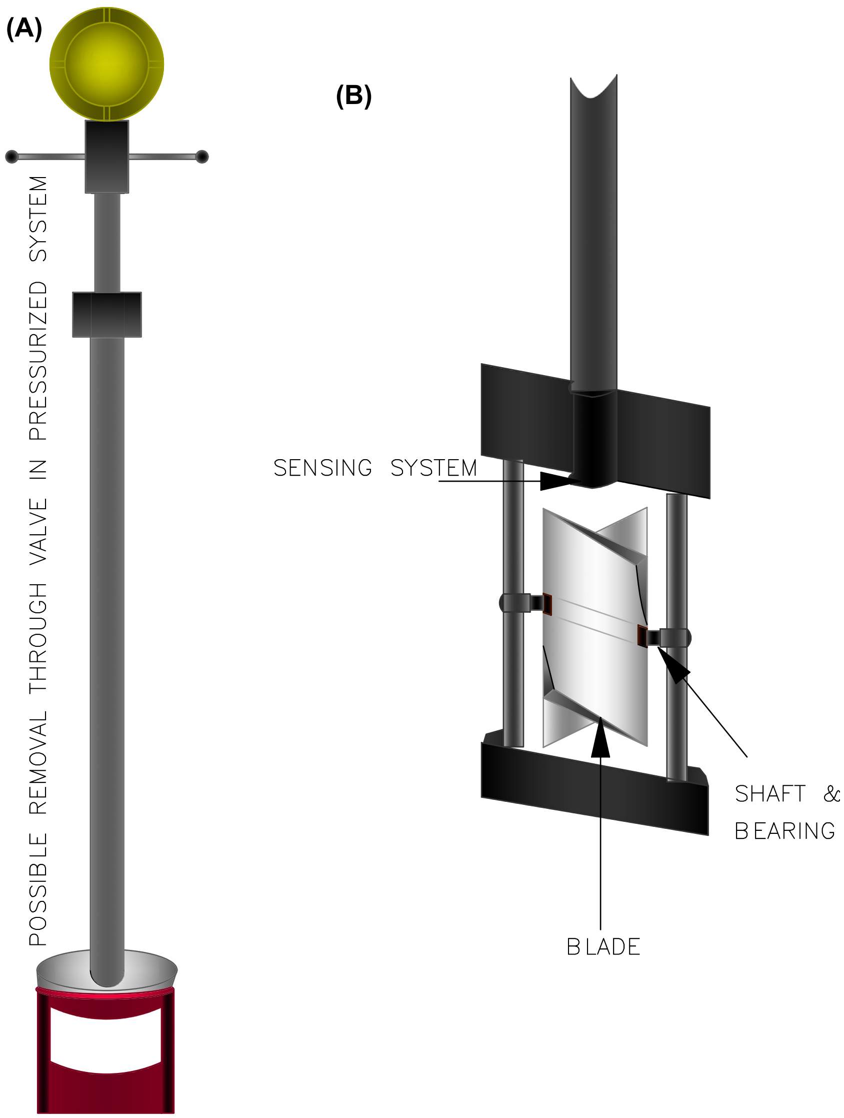


FIGURE V/2.8.0-1 Typical insertion turbine GA and internals. (A) Typical insertion turbine. (B) Typical insertion turbine details. *Developed based on an idea from ONICON insertion type turbine details. Courtesy: ONICON.*

1. **Process conditions:**
   - *Pressure rating:* up to 200 bar;
   - *Temperature:* −50 to 160°C;
   - *Flow:* Gas: 50 m^3/s; liquid: 15 m^3/s;
   - *Viscosity:* Low viscosity.
2. **Material:** Stainless steel, nickel-plated brass.
3. **Process connection:** Screwed/flanged.
4. **Performance (best values):**
   - *Accuracy:* 0.5% FSD;
   - *Repeatability:* 0.2% FSD;
   - *Linearity:* Around 1% up to 5 cSt viscosity.
5. **Pressure loss:** Low <0.1 for velocity up to 7 m/s.
6. **Mounting:** Horizontal/vertical.
7. **Insertion/withdrawal:** By hot tap adapter/isolating valve.
8. **Overhead clearance:** As per manufacturer's recommendation.
9. **Tapping size:** 25 mm normal.
10. **Sensing:** Hall effect/optical or other nonmagnetic (impedance sensing).
11. **Electrical details:**
    - *Field-mountable:* preamplifier and frequency to current converter;

- *Power supply:* 24 VDC;
- *Electrical connection:* ½″ Et/NPT.

12. **Application area:**
    - Condensate flow;
    - Feed water flow;
    - Chilled water flow in HVAC;
    - Hot water;
    - Make up water;
    - Cooling tower;
    - Municipal water.

2.8.2 GAS TURBINE FLOW METER

During the discussion in Section 2.1.6 it has been shown that as the density is low for gas and they have to handle higher velocity, there have been a number of changes to gas turbine flow meters. Also, the rangeability of gas turbine flow meters also has a high turndown ratio (100:1 is common) compared to normal inline TFMs. Use of ball race bearings (in place of journal bearings of liquid TFMs) is another distinctive feature in gas turbine flow meters (GTFMs). These bearings are sealed to protect them from dust normally found in gas. EN 12261 standard provides guidelines for gas flow measurement through TFM.

1. **Principles of operation:** Gas turbine flow meters (GTFM) basically consist of a rotor assembly with accessories, housing, and digital head index. GTFMs have an integral upstream multistage flow conditioner (for removal of undesirable swirl and asymmetry prior to entry to freely rotating turbine) and a diffuser for accelerating the condition of the gas entering the meter. The dynamic forces of the flowing gas cause the rotor to rotate. The turbine wheel is mounted on the main shaft, with high-precision, low-friction ball race bearings already mentioned earlier. The turbine wheel has helical blades that have a known angle relative to the gas flow. As with liquid TFM, here gas flow drives the turbine wheel at an angular velocity, which is proportional to the gas velocity. The rotating turbine wheel drives the mechanical counter through magnetic coupling and gear. Thus a high-frequency (HF) pulse transmitter is responsible for local indication. Typical GTFM components are shown in Fig. V/2.8.0-2A.

   As shown a Reed contact/an inductive sensor located on the digital index box generates low-frequency pulses proportional to the volume flow at operating condition for the flow of the gas that is being measured. To take care of volume variations at different operating conditions, pressure and temperature measurements are carried out so as to calculate the flow at a given base condition. Pressure and temperature tappings for the measurement have been shown also. Gas turbine flow meters also have a lubrication system (not shown). In many GTFMs there is one reference wheel (CAM) kept on the same shaft for the purpose of monitoring the turbine. There are two HF pulse transmitters, namely, HF2 (monitoring) and HF3. In the case of a total electronic meter, as in TRZ 03-E of Honeywell, there is no meter head, there will be only two HF pulse transmitters.
2. **Operating conditions:** Maximum operating pressure could be 100 barg. So, meters are available in pressure PN 10 through PN 100 (ANSI150 through 600) also and can operate at temperatures between −10 to 50°C.
3. **Meter sizes and flow range (turn down):** Flow ranges and turndown: Meters are available from DN 50 to DN 600 to cover max flow of 40,000 m^3/h. However flow is dependent on the operating conditions and would be different for different gases, so it is specified as 10 m^3/h (atmospheric air), 5 m^3/h (natural gas at 4 bar), and 3 m^3/h (natural gas at 8 bar). These are given here from actual data of an available meter and to show how flow varies with operating conditions and density. Normally, turndown ratio of 100:1 is common. Some manufacturers also have higher flow ranges and sizes, e.g., Badger meter Cox model size of 32 to cover flow of 250 acfm.

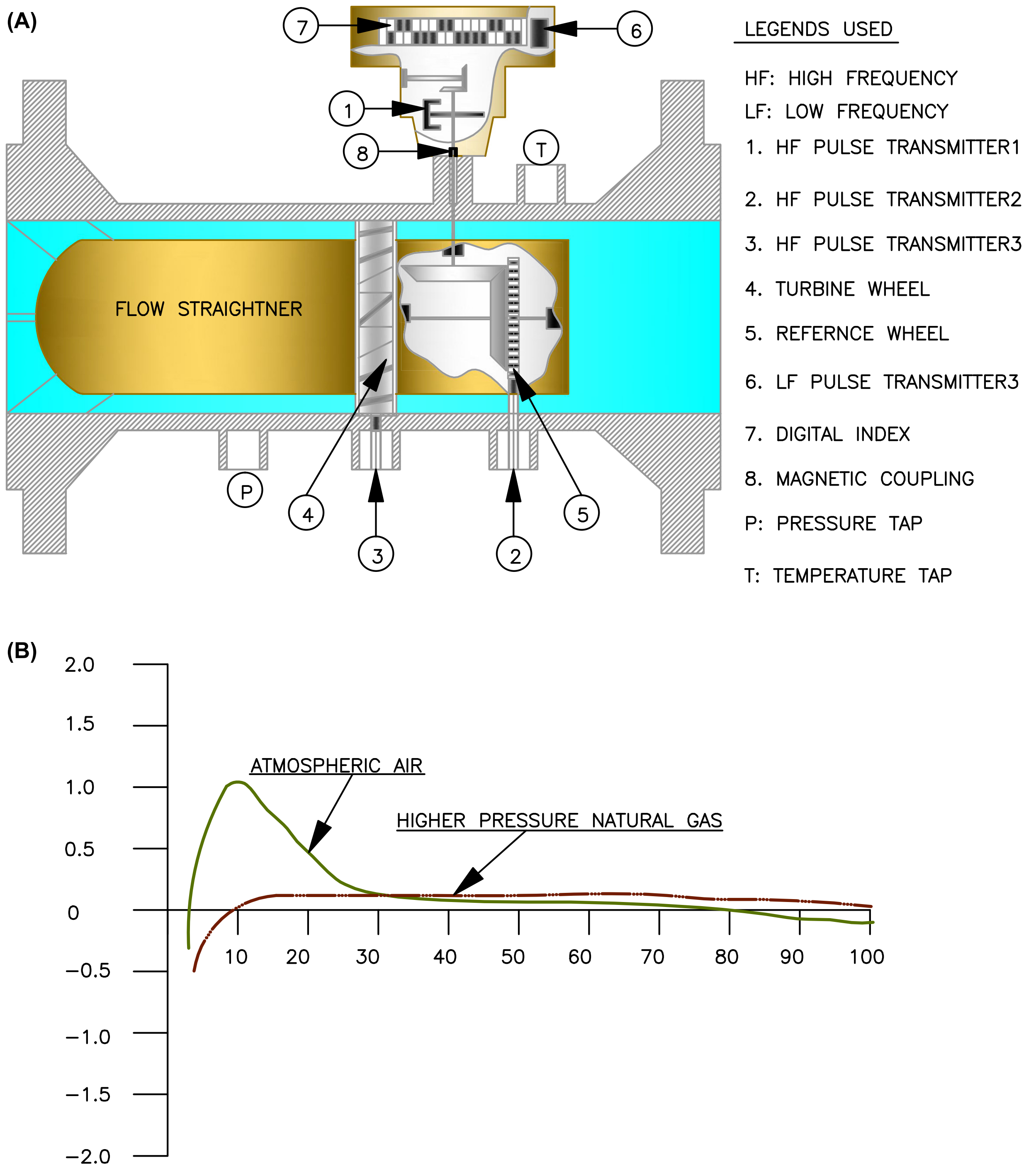


FIGURE V/2.8.0-2 Gas turbine flow meter. *Developed based on an idea from TRZ03 OF RMZ. Courtesy: Honeywell.*

4. **Performance data:** The following are some important performance data for GTFMs.
   - *Accuracy (Min):* 0.2 q_{max} to q_{max} = 1%AR; $0.2q_{min}$ to q_{max} = 2% AR;
   - *Repeatability:* 0.2% AR or better;
   - *Response time:* 15–30 ms.
5. **Calibration:** GTFMs are tested with atmospheric air to traceable calibrated references. Meters can be calibrated with natural gas at higher pressures, with test installations traceable to primary standards. As the calibration accuracy, etc. depends on operating conditions and gas density, the accuracy level varies; these are referred to as metrological effects/characteristics, as shown in Fig. V/2.8.0-2B. It is essential to calibrate the gas turbine meter initially, preferably under simulator operating conditions, to establish their own specific K factor [9]. As the meter-bearing characteristic varies, calibrations should be carried out at regular intervals.
6. **Pressure loss:** Pressure loss is a function of gas density. Pressure drop at q_{max} is normally available from the manual. So, from there pressure drop at various conditions can be calculated from Eq. (V/2.8.2-1):

$$\Delta P_2 = 1.667 \times (\Delta P_1 \cdot d_r) \cdot \left(\frac{P}{P_{atm}}\right) \cdot \left(\frac{q}{q_{max}}\right)^2 (P_{abs}) \qquad \text{(V/2.8.2-1)}$$

   where, ΔP_2 = pressure drop at P and Q_{max}; ΔP_1 = pressure drop at Q_{max} (as per manufacturers standard provided in the manual); P = operating pressure of the meter in bar absolute; P_{atm} = atmospheric pressure in bar absolute (1.01325 bara); q = instantaneous flow in m^3/h; q_{max} = maximum flow rate in m^3/h; q_{min} = minimum flow rate at atmospheric pressure in m^3/h, d_r = relative density of the gas (air = 1).
7. **Lubrication:** Meters are also equipped with a lubrication system consisting of a lubrication reservoir and pump. In the case of occurrence of condensate in gas and/or for dust-laden gas, frequent lubrication is recommended.
8. **Sensors:** As seen there are a numbers of sensors in GTFMs. There are two kinds of HF and LF pulse-transmitting devices. LF signal is an inductive/Reed switch sensor for remote transmission. There are three HF pulse transmitters:
   - *HF1:* With the help of gear/magnetic coupling used for digital head index.
   - *HF2:* This HF sensor is located on the shaft or reference wheel for monitoring of the turbine. This high-frequency sensor generates signals and as such the flow direction can be monitored.
   - *HF3:* Located at turbine wheel, can be used to check the condition of the turbine wheel (missing blades) by comparing the pulses with the HF main shaft.
9. **Materials:** Typical materials used for GTFM are as follows:
   - *Body:* Lightweight aluminum/steel/low-temperature steel—CS;
   - *Cartridge, vane, and wheel:* normally aluminum; rotor can be of 17-4 PH stainless steel;
   - *Shaft/bearing block/bearing:* Stainless steel (316); ceramic bearing is also used.
10. **Gas types:** Normally used for various types of gases with use of suitable materials; a few common gases are fuel gases, such as natural gas, refinery gas, gaseous liquid gases, and their mixtures, nitrogen, CO_2 (dry), air, and all inert gases. Normally in the product manual a list of usable gases is available. Normally this list is wide enough to accommodate almost all gases normally encountered during industrial use.

2.8.3 DOUBLE-ROTOR TURBINE FLOW METER

This particular name in reality ***does not apply*** to any flow meter. Actually this name has been specifically used to indicate that there are two design types where two rotors are used in contrast to single-rotor turbine meters discussed so far.

These types of meters are known as twin-rotor design and dual-turbine design. It is worth noting that both these designs are meant to measure *volumetric* flow. Also they were not very popular outside the aerospace industry. One should not confuse these with twin turbine mass flow meters discussed in Chapter VI. In the case of *twin-rotor design*, there are two identical turbines. In the case of dual-turbine design, the two turbines are of two different designs, each with its own shaft and bearing. In fact, dual-turbine design is one recent development of the turbine flow meter. There are two classes of dual-turbine design and these are dual turbines rotating in (1) the same direction and (2) counter-opposed rotation. These types of dual designs can be utilized for both liquids and gases. The main aim of the recent development of dual-rotor flow meters was to meet the requirements of industry for wider operating flow ranges, improved performance, i.e., repeatability, absolute accuracy, and lower cost installation. With a higher incidence angle on the rear rotor it is possible to measure lower flow rates with better performance [13]. Thus the meter gives increased turndown ratio. In dual-rotor turbine flow meter design, it is possible to enhance universal viscosity curves (UVCs) also.

1. **Twin-rotor design TFM:** The twin-rotor design finds its application in military installations on jet engine test stands and on interservice flow transfer applications under US Navy/NBS auspices and is used in flow meter "prover" applications to check the calibration and accuracy of other flow meters [9]. These types of flow meter provide a high turndown ratio as high as 200:1. Here there are two identical turbines. The rear turbine is connected with a sensor shaft. The front turbine rotates the shaft in the same direction, to minimize relative velocity between the two. The rear turbine actually does the main work of driving the shaft on which the upstream turbine *bearing* ride. There is another kind, better known as electronic twin-turbine design. In this design there are two identical independent turbines. There will be continuous comparison of these two turbines, and this will enable to detect even the smallest deviation. Electronic twin-turbine meters are available with batteries for operation in remote places. Electronic twin-turbine meters are mainly used in gas flow measurement. These are available in meter sizes up to 300 mm, to cover a flow range up to 7500 m^3/h, with an accuracy as high as 0.1% AR. Since this type of meter is meant for gas flow meters, similar metrological characteristics discussed in Subsection 2.8.2.5 are applicable here.
2. **Operation of dual-turbine rotating in opposite direction:** The dual-rotor turbine flow meter consists of two closely coupled rotors with counter-opposed blade angles in a single shaft for rotation. The two rotors are hydraulically coupled. Swirls of fluid from the first rotor exit affect the incident angle of the rear rotor. Fluid swirls of the first rotor have an opposite effect on the rear rotor and fluid swirl incidents on the rear rotor are almost at a right angle. On account of the opposite effect of swirl on two rotors, when the front rotor speeds up, due to hydraulic coupling in the opposite direction, the rear rotor will slow down by the same percentage (and vice versa). There are sensors at both rotors. Therefore, the sum or average of the signal output represents the actual flow rate, regardless of the swirl effect on rotor revolutions/speed. There are both pros and cons. Flow straighteners/conditioners, including upstream/downstream straight pipe run are not required in most applications. So, flow distortions which could affect the meter performance can be eliminated. This enables the meter to be installed in limited space. This method improves the rangeability of the meter at the same time as makings the bearing vulnerable at low flow rate when the rear turbine has to run at high speed [9]. There is a suitable lubrication system of bearings for TFMs. The signal from the sensors is processed in a flow computer, which by

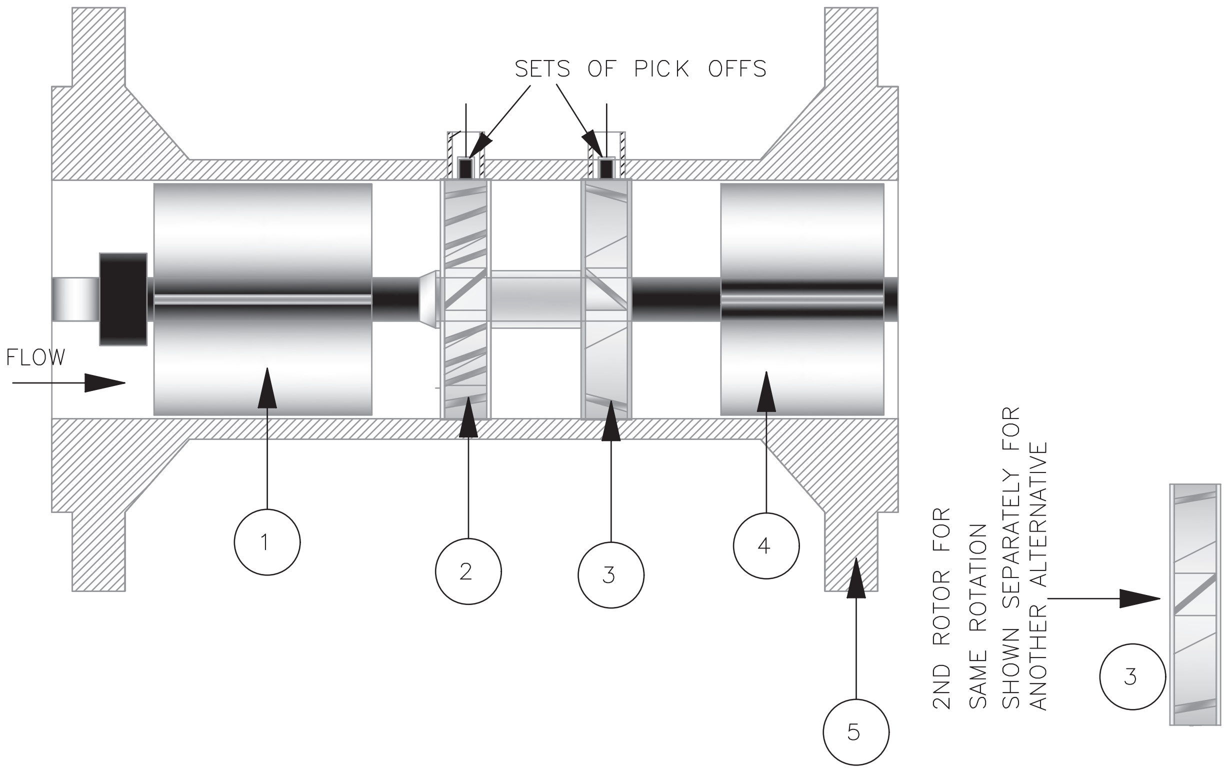


FIGURE V/2.8.0-3 Dual-rotor TFM. (1) Straightening vanes, (2) first rotor, (3) second rotor for opposite rotation, (4) flow exit, (5) flange process connection.

monitoring the output ration of frequency from the front and rear rotors helps to determine bearing contamination and diagnose bearing defects. On account of the larger central hub and narrow annulus a turbulent flow regime is promoted. However, increased velocity obviously causes a higher pressure drop. A typical cross-sectional view (schematic) has been depicted in Fig. V/2.8.0-3. Since there are two types of dual rotor design, there are two different rear rotors, and so one is shown separately in Fig. V/2.8.0-3 for a dual-rotor TFM.

3. **Operation of dual turbine rotating in the same direction:** In this design also there are two independent rotors placed close to each other. The front rotor is the main driving rotor and the rear rotor, which has a much lower blade angle, is the sensor rotor. There is continuous correction of measurement errors due to varying bearing friction as the flow rate based on the difference between the rotor speeds. The major difference in this design to opposed rotation dual turbines is that the two rotors have ***independent*** shafts and measurement is carried out in terms of difference of speed of two turbine rotors. The front turbine has a higher blade angle and the rear turbine has a much lower blade angle. As a result of this the front turbine rotates at a higher speed than the rear turbine. Another interesting thing is that the meter is rather insensitive to the swirl effect [14]. This is because of the fact that any swirl effect will affect both meters in the same way, and the flow rate is calculated on the basis of ***difference***, so the swirl effect of one cancels the effect on the other. When the front turbine moves slower due to wear in the *bearing*, the exit angle fluid will change and as a result the rear turbine adjusts its speed by an equal amount [9]. It is possible to check bearing wear and faults by monitoring the ***ratio*** of the two rotor speeds.

4. **Features of dual-rotor turbine meters:** The following are various features of dual-turbine meters.
   - *Absolute accuracy:* Superb accuracy with higher turndown ratio;
   - Excellent speed of response with nominal pressure drop;
   - Extended Universal viscosity curve (UVC) range.
5. **Application areas of dual-rotor turbine meters:** The following are major application areas.
   - Custody transfer application;
   - Master meter for other meter calibration;
   - Correlation standard.
6. **Technical details and operating conditions:** The general technical data from a reputed manufacturer [15] (Courtesy: Badger meter are given here.
   - Process connection screwed (NPT) and flange connection of international standard;
   - *Pressure drop at full flow:* Around 1 barg at maximum flow;
   - *Operating pressure:* As high as 220 barg;
   - *Operating temperature:* −200 to >150°C;
   - *Flow and meter Size:* Refer to Table V/2.8.3-1.
7. **Materials of construction:** The following are the major materials used:
   - *Shaft body support:* Stainless steel (316/302 for support);
   - *Rotor:* 17-4 PH stainless steel;
   - *Bearing:* Ceramic, better performance for lower friction.
8. **Typical performance data for a dual-rotor design:** The following are typical performance details:
   - *Absolute accuracy:* 0.1% AR;
   - *Repeatability:* 0.02% AR;
   - *Linearity:* 0.1% AR (with a flow computer).

2.9.0 Other Inferential Flow Meters

There are a few other inferential flow meters used in industries and process plants. These will be discussed in this section. The discussion starts with the paddle wheel flow meter.

2.9.1 PADDLE WHEEL FLOW METER

The paddle wheel flow meter is one of the least costly flow meters, developed for inserting in pipe fitting either as an inline or insertion type. A typical paddle wheel arrangement has been depicted in Fig. V/2.9.1-1. These meters are available in different sizes up to 300 mmNB. There are three basic parts/components of paddle wheel flow meters; these are the paddle wheel sensor, the pipe fittings, and the display/controller. The paddle wheel is basically a freely rotating wheel/impeller with embedded magnets, which is fitted perpendicular to the direction of flow. In the flowing medium, the wheel rotates; naturally the embedded magnets in the blades also rotate and spin past the sensing coil. On account of the changes in lines of forces of the magnet electromagnetic flow (EMF) is generated in the coil. So, the output generated in the coil will have its frequency and voltage proportional

TABLE V/2.8.3-1 Typical Meter Sizes and Flow Ranges

Meter Size	Flow Range LPM	TD Ratio	UVC TD Ratio	K Factor Front	K Factor Rear
½″	0.13–37.8	286:1	40:1	9480	10,440
1″	0.37–246	433:1	60:1	1680	1846
2″	1.7–1173	517:1	60:1	242	266
4″	18.9–5678	300:1	60:1	20	22

The reader should note the relation of UVC TD ratio and K factors with size and flow range.
K factor represents pulses per gallon.
Courtesy: Exact Flow.

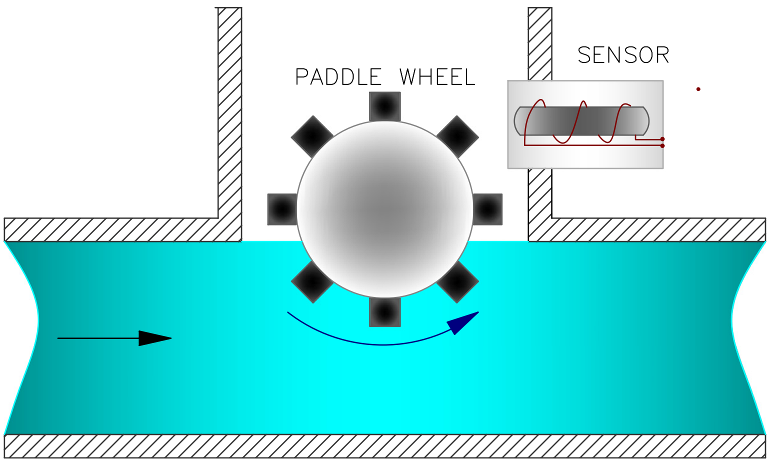


FIGURE V/2.9.1-1 Paddle wheel flow meter.

to the flow rate. In some cases in place of magnetic sensors, optical sensors are used. The outputs from the sensor signal conditioning unit, pulse, or standard analog outputs are produced. The paddle wheel can sense from a very high velocity to as low as 0.1 m/s (e.g., Signet 2537 paddle wheel flow meter).

Another advantage of this meter is that it requires much less straight pipe length than is required for turbine meters. Salient features specifications and application areas for this meter include but are not limited to the following.

1. **Advantages:**
   - Low-cost solution for moderate accuracy flow measurement;
   - Easy to install and operate;
   - On account of very low pressure drop, can be used for gravity flow.
2. **Disadvantages:**
   - Not suitable for gas flow or for high viscous liquid;
   - Some claim slurry application, but would need frequent cleaning [9];
   - Straight run of pipe necessary to create swirl pattern;
   - Not suitable for partially filled pipe as air will create inaccuracy.
3. **Specification:**
   - Turndown 20:1;
   - *Accuracy:* 2% FSD available;
   - *Working pressure:* >10 bar;
   - *Working temperature:* >50°C;
   - *MOC body paddle axel:* Metallic: SS; nonmetallic: PVDF.
4. **Application areas:**
   - Process flow monitoring;
   - Chemical process;
   - Pump protection;
   - Filtration, reverse osmosis, and pure water monitoring;
   - Water treatment plants;
   - Cooling towers and scrubbers.

2.9.2 WOLTMAN FLOW METER

From an operational point of view there is no difference between a turbine meter and a Woltman meter. The basic difference comes from the method of sensing the rotation of a turbine. Unlike in a turbine meter, rotation of the rotor is not measured directly but instead through a mechanical link it is transmitted upward to the gear trains where the rotation is measured mechanically or sensed via a magnetic sensor to produce the necessary outputs for rate indication and totalization. In Woltman the rotor axle is parallel with the direction of flow, i.e., to the turbine wheel. There are two versions of Woltman flow meters: vertical and horizontal.

The vertical version as shown in Fig. V/2.9.1-2 and has the advantage of lower friction and hence higher sensitivity. Fig. V/2.9.1-2 also shows the allowed installation styles. On account of flow

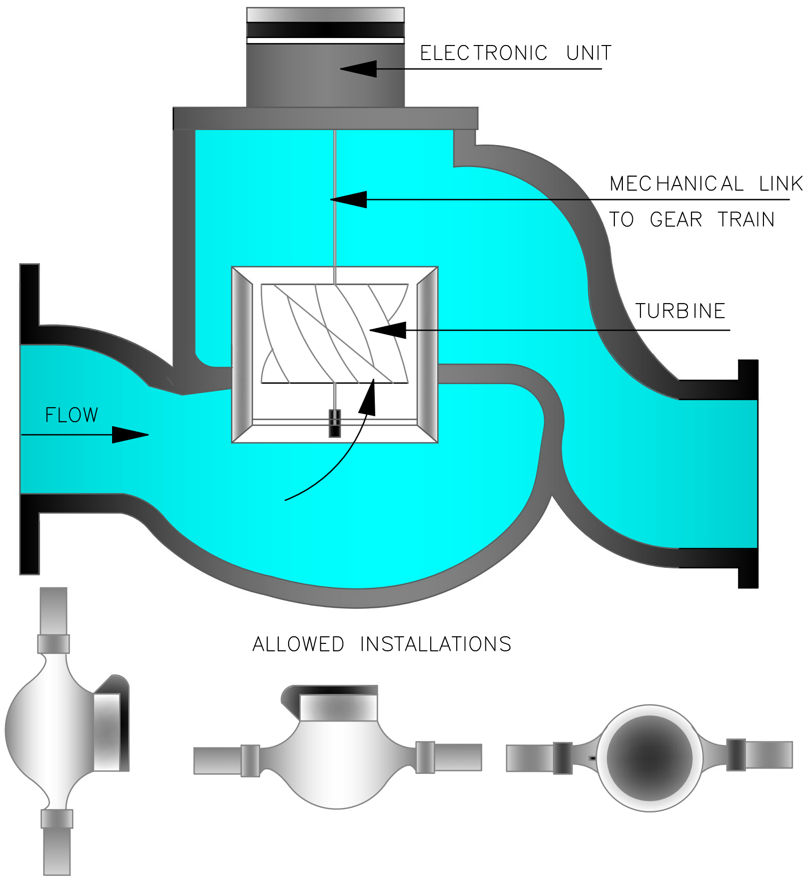


FIGURE V/2.9.1-2 Woltman flow meter.

passage, the pressure loss is greater in this version. At the lower measuring range of flow, the vertical version may have greater error, but in the normal flow range both offer a similar level of errors. Also, there two design types: single jet and multijet. Multijets are mostly seen in larger meters (>20 mm). The pressure- and temperature-withstand capabilities are around 10 bar and 90°C, respectively. The sizes start from 15 through 200 mmNB to cover a wide capacity range from nearly 3 to 400 m^3/h. The Woltman totalizer is used mainly as a water meter. Meters are also available in an IP68 enclosure.

With this the discussions on inferential flow meters come to an end and we start discussions on vortex/swirl type flow meters—another velocity-sensing meter with wide applications.

3.0.0 VORTEX AND SWIRL TYPE FLOW METERS

Vortex shedding was noted when a large class of obstacles were placed in natural stream. Oscillating vortices occur when a fluid stream passes a bluff body (nonstreamlined). The frequency of the vortices depends on the size and shape of the body. A systematic study was done by the mathematician, Tódor von Kármán (1881–1963), who in 1911, described the stability criterion for the array of shed vortices. Consequently, a repeating pattern of swirling vortices caused by the unsteady separation of flow over obstacles or bluff body was named after him and referred to as ***Von Kerman vortex street***.

3.0.1 VORTEX FLOW MEASUREMENT THEORETICAL BACKGROUND

Von Kerman made observations that when flowing streams comes across a nonstreamlined object or bluff body in the path of a flowing stream, the fluid is unable to remain attached to the obstruction on its downstream sides. Eddies with Reynolds number Re $47 < Re < 10^7$ shed continuously from each of the bodies forming a row of vortices in its wake. The slow-moving fluid in the boundary layer on the bluff body becomes detached on the downstream side and rolls into eddies and vortices. These "shed" vortices are carried downstream in the flow and are detected by vortex shedding and fluidic flow meters.

Initially the study was carried out in unconfined flow. Von Kármán observed that the distance between the vortices, i.e., wave length, is a function of width of the object irrespective of fluid flow velocity. Again, the faster the flow, the faster will be the vortices formed. Later Strouhal determined that, as long as the Reynolds number of the flowing stream was between 20,000 and 7,000,000, the ratio between the shedder width (d) and the vortex interval (1) would be 0.17 [9]. Finally with the use of dimensionless Strouhal number (St, named after Strouhal) the relationship between vortex shedding frequency (f) and fluid velocity (v) for an object of width d was established.

$$v = \frac{f \cdot d}{St} \quad \text{(V/3.0.1-1)}$$

Later, the same principle was applied to fluid in confined pipes, where the same relationship holds good. Here, in the case of pipe applications, average velocity is used.

So, volume flow in a pipe of internal cross-section A and average velocity v (which should be represented correctly as $\bar{v}$) will be given by q (or q_v) $= A \cdot v$. Since A is a constant for a pipe, thus flow q α v. From the above discussions, utilizing Eq. (V/3.0.1-1) one gets $q = A \cdot \left(\frac{f \cdot d}{St}\right)$. After rearranging the constants together one gets the flow equation as

$$q = \left(\frac{d \cdot A}{St}\right) \cdot f \text{ or, } q = \frac{f}{K} \quad \text{(V/3.0.1-2)}$$

where the K factor is given by $K = \frac{St}{d \cdot A}$.

The frequency range found in the vortex shedding meter ranges from as low as 1 Hz for a larger meter with low velocity to as high as 3 KHz for smaller meters with higher velocity. Now the mass flow (q_m) can be computed by multiplying the volume flow equation with the flowing medium density at operating conditions. So, by using Eq. (V/3.0.1-2),

$$q_m = q \cdot \rho_{op} = q_v \cdot \rho_{op} = \frac{f}{K} \cdot \rho_{op} \quad \text{(V/3.0.1-3)}$$

Normally, volume flow (especially for gas/steam flow) is computed at a base condition, e.g., at NTP/STP, etc. Therefore, it is necessary to convert the signal into base condition with suitable pressure/temperature compensation (already covered in Chapter I). Therefore, at base condition mass flow will be computed from Eq. (V/3.0.1-3) as:

$$(q_m)\text{base} = \frac{f}{K} \cdot \frac{\rho_{op}}{\rho_{base}}$$

where ρ_{base} = density at base condition; and ρ_{op} = density at operating condition.

Here there are variations in mass measurement. Some designs detect mass flow by detecting the vortex frequency and vortex *pulse strength*. From these two readings the process density can be determined to compute the mass flow [16]. Other types use multiple sensors to detect the vortex frequency for flow measurement and the pressure/temperature of the process fluid. All these data help to detect the volume flow and fluid density required for computing mass flow, as already discussed.

3.0.2 SYSTEM REQUIREMENTS FOR VORTEX FLOW MEASUREMENT

Flow measurement by vortex meter is based on a number of system conditions and system requirements as listed here.

1. Pipe Reynolds numbers should be sufficiently high to produce vortices.
2. Bluff body should be such that the geometry of the vortex formation does not change with the flow rate [1] and bluff body should not be eroded or get coated by process fluid.
3. From the velocity equation, it is noted that the Strouhal number should be constant. However it is not so, it has *variations* with the *Reynolds* number, and such variations are affected by the *shape* of the bluff body chosen. Therefore, the Strouhal number should remain constant over a wide Reynolds number range.
4. Vortex intensity should be strong and/or the sensor should be sensitive enough to detect these vortices.

When the above requirements are fulfilled then the flow meter will be sensitive to velocity only and insensitive to the nature of fluid, such as liquid/steam or gas, and to the fluid properties, like density, viscosity, etc. Here one thing to be noted is that some gases like H_2 produce vortices with weak force [9] so, in these cases the sensitivity of the sensor is important. In the above discussion it has been stated that the Strouhal number should be constant over a range of Reynolds number, thus there will be variation of the same with the Reynolds number as shown in Fig. V/3.0.2-1. Since the Strouhal number is a constituent element in K factor, so the K factor will also have variation with Reynolds number. This variation of K factor over a selected Reynolds number range is sometimes referred to as linearity. However, variation of K factor in percent is very nominal for Reynolds number lying between 10^4 and $>10^6$, hence sizing should be done accordingly. At Reynolds numbers below the linear range, linearization is possible but flow meter uncertainty may be degraded [17].

3.0.3 CONCEPT OF SENSING

On account of vortex, both the pressure and velocity fields near the shedder will oscillate at the vortex shedding frequency, i.e., the vortices generate periodic pressure and velocity variations. Therefore both pressure and velocity sensors can be used for sensing the oscillating field in electrical output. This means that there will be dynamic pressure because shedding has taken place or the shedder bar is excited by the kinetic energy of the flow. Thus from Bernoulli's energy equation, this dynamic pressure can be expressed as

$$P_d = 1/2\rho_{op} \cdot v^2 \quad \text{(V/3.0.3-1)}$$

here P_d = dynamic pressure; ρ_{op} = density of flowing fluid at operating condition; and v = velocity of flowing fluid. Variations of dynamic pressure variations have been elaborated on in Section 3.1.3. Here a few things to be noted are that the dynamic pressure sensitivity of the meter (1) is proportional to density (and may

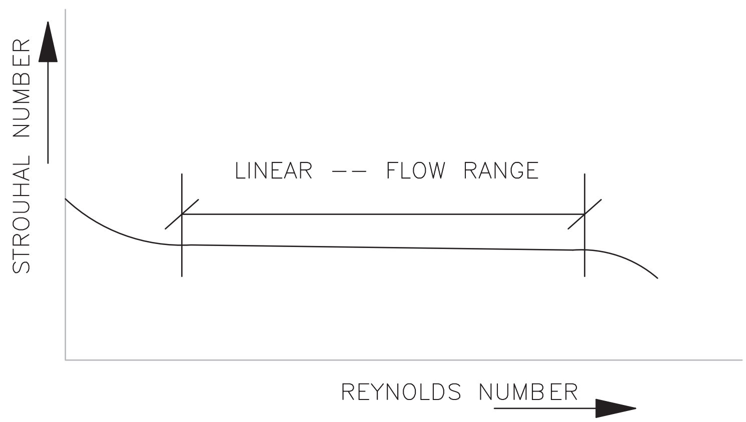


FIGURE V/3.0.2-1 Strouhal number versus Reynolds number.

vary with temperature) and (2) is proportional to square of velocity. Thus from these one can conclude that the dynamic pressure sensitivity of the sensor must be very large, because for a turndown of velocity 20:1 the dynamic pressure sensitivity of the sensor would be 400:1 (square relationship). Also, these vary with the density of the medium. The amplitude of the dynamic pressure has been depicted in Fig. V/3.0.3-1.

From the above discussions it transpires that both pressure and velocity sensors can be used for sensing the oscillating field in electrical output. The sensor can be placed behind the bluff body or in the bluff body so that free vibration can be sensed. There are many choices of sensors, such as mechanical, DP measurement, capacitive, piezo-element, ultrasonic, thermister, etc. Even though there are many choices of sensors, there is *no* single sensor which can cater to *all* the operating conditions [5]. The sensor placement location is decided by the diameter and type of connection [1].

3.0.4 SWIRL/VORTEX PRECISION METER

A guide body in the form of swirl-inducing vanes with a shape similar to a stationary turbine rotor (see swirler in Fig. I/3.1.3-2) at the entrance to the meter introduces a spinning or swirling motion to the fluid and forces the fluid entering the meter to spin about the center line. At the exit of the swirl vanes, swirling fluid flow passes through a Venturi. So, first in the contracting bore, the fluid first accelerate, with the axis of rotation still on the center line of the meter. Then the swirl stabilizes in the cylindrical section of the meter tube. After the cylindrical section, the swirling fluid then enters an enlarged section where the axis of

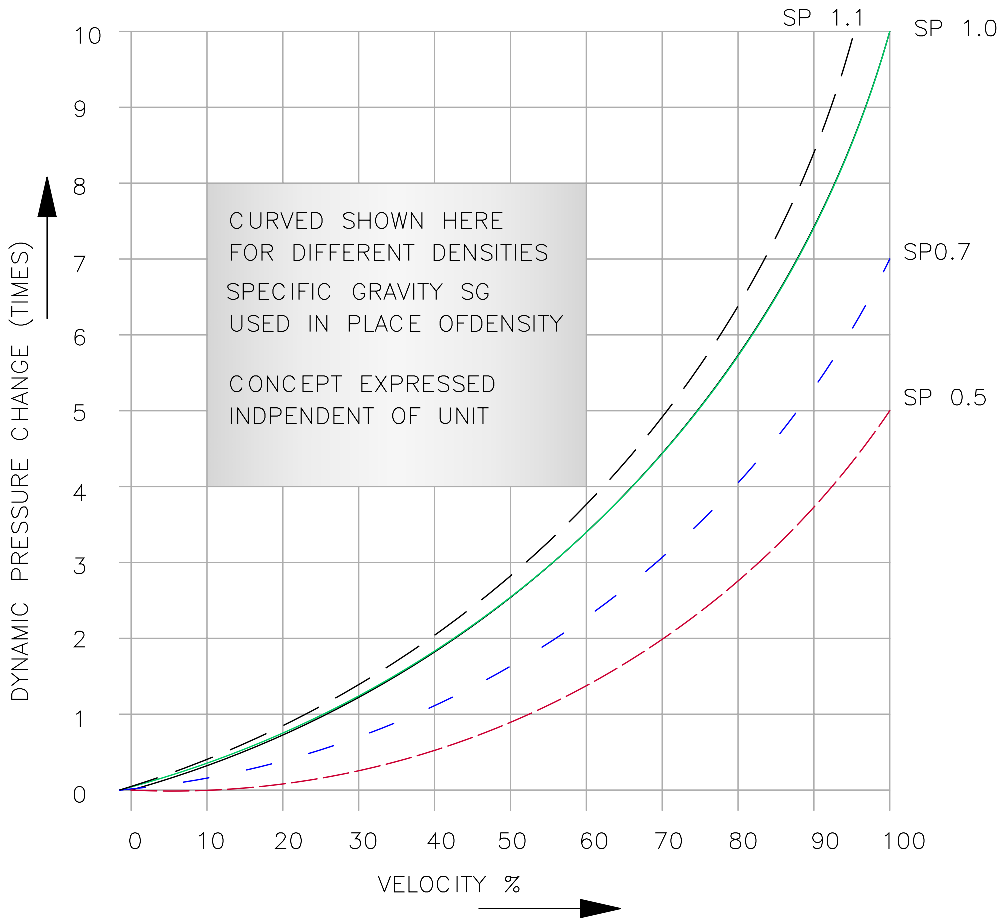


FIGURE V/3.0.3-1 Dynamic pressure sensing.

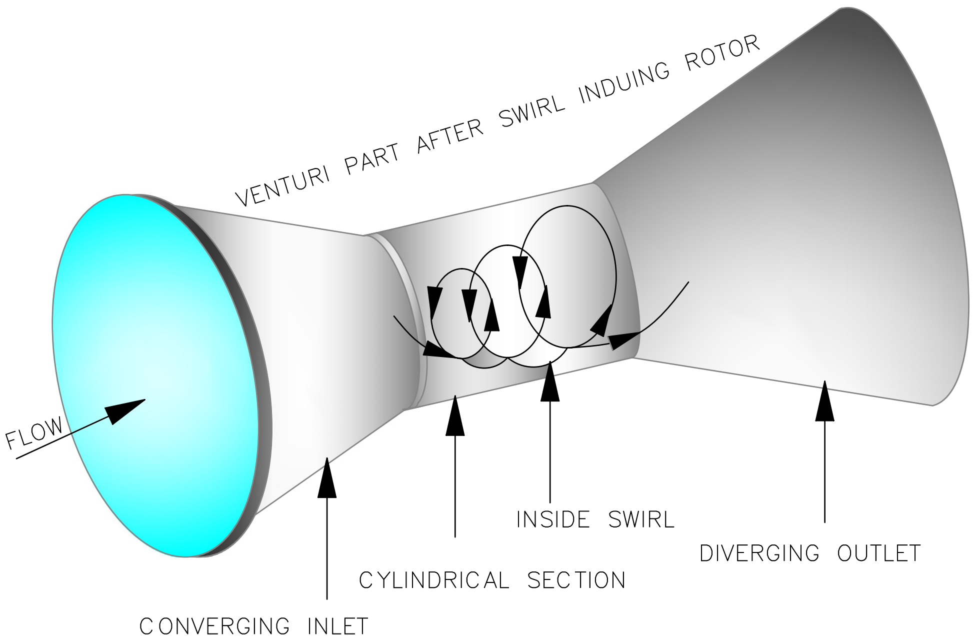


FIGURE V/3.0.4-1 Flow in swirl meter.

fluid rotation changes from a straight to a helical path. In this manner the measuring medium is forced to rotate and flows through the meter tube of the swirl flow meter in a thread-like rotation [1]. This spiraling vortex is popularly known as ***vortex precession***. At the cylindrical part the rotational velocity at the wall is relatively small and increases toward the tube center until a stable vortex core is formed at the center. The vortex core forms a spiral-like secondary rotation whose frequency is linearly proportional to the flow rate over a wide range [1]. For better understanding the Venturi part of the meter with swirl inside, see Fig. V/3.0.4-1. The "swirler" has at its core a low-pressure zone. This low pressure zone is thrown into a secondary rotation proportional to flow rate. The piezo element sensor is used to detect the frequency of the secondary rotation, by the patented manufacturer. However other sensing method could be utilized.

The swirl meter poses challenges to vortex flow metering technology existing nearly decades in terms of better accuracy, higher turndown ratio, etc.

3.0.5 SWIRL METER AND VORTEX METER

Although both the vortex meter and swirl meter work on the principles of vortex shedding, there are a few advantages of swirl meters for which it could throw challenges to years-old vortex meter technology. Comparison of various characteristic features of both meter types have been enumerated in Table V/3.0.5-1 to highlight the advantages of a Swirl meter.

TABLE V/3.0.5-1 Comparison of Swirl Meter and Vortex Meter

Point of Difference	Swirl Meter	Vortex Meter
Pipe straight length	Can create own profile. Upstream length: 3D and downstream length: D	Upstream: 15D, Downstream: 5D
Flow velocity	Can work with lower velocity, as the meter has own flow Venturi	Normally use smaller meter to get higher velocity

Continued

TABLE V/3.0.5-1 Comparison of Swirl Meter and Vortex Meter—cont'd

Point of Difference	Swirl Meter	Vortex Meter
Turndown ratio	30:1	20:1
Viscosity	30 cP	<10 cP
Accuracy	Better than vortex meter	
Twist	Own flow conditioning, hence easier installation requirements	More installation requirements
Low flow	Not good for low flow registering	
Interference	Disturbed by external interferences like vibration EMF hydraulic noise	

This table is based on an idea from Swirl Versus Vortex Flow Meter Technology, Application Description AG/FS/FV_101-EN, ABB Limited, 2012. https://library.e.abb.com/public/38a6e019bd68bdf5c12579d400405903/AG_FS_FV_101-EN-03_2012.pdf. Courtesy: ABB.

3.1.0 Descriptive Details of Vortex/Swirl Flow Meter

To understand the operation of a vortex flow meter it is necessary to go through the discussions detailed in Subsection 3.1.3.2 of Chapter I and details in Section 3.0.0 in this chapter.

3.1.1 PRINCIPLES OF OPERATION

The operating principles of vortex and swirl meters are the same. Only in the input section are there certain differences discussed in Section 3.0.4 above which make the swirl meter more accurate.

1. **Vortex meter:** When one recalls the discussions in Section 3.0.0, when a nonstreamlined bluff body is placed on the path of a flowing stream with adequate Reynolds number, the flow will alternately generate vortices either side of the bluff body. In a vortex meter, the bluff body is a piece of material with a broad flat front (with respect to the back of it) and the bluff body extends vertically in the flow stream. The frequency at which these alternate vortices will be generated is proportional to the flow velocity. On account of the generation of these vortices, there will be changes in dynamic pressure (Section 3.0.3). These changes in dynamic pressure (the periodic pressure and velocity variations) or vortex force are measured with the help of a suitable sensor. Therefore the sensor will produce suitable electrical pulses whose frequency is proportional to the flow velocity (see Section 3.0.0). The flow rate is calculated by multiplying the area of the pipe by the velocity of the flow. In the case that the density of the flowing medium at operating condition can be measured/ascertained, then mass flow can be computed. Normally density of the flowing medium is manual input for the computation. Naturally, to get the correct flow at various operating conditions of pressure and temperature, these two parameters are also measured (see Section 3.0.1). For many vortex meters there are provisions for temperature measurement as well as optional pressure measurement (required for gas/steam) of the fluid along with flow measurement (i.e., temperature and pressure sensing built in with the meter). So, when these compensating units are built in then it is possible to obtain mass flow at operating conditions. Another important issue is that if there is distortion in the flow profile, there will be requirements for a long straight run of pipe for the vortex to operate accurately.

2. **Swirl meter:** As stated earlier, in the case of a swirl meter there will be an inlet flow conditioner i.e. in Swirl flow meter incoming fluid is forced through a fixed swirl inducing element located at the upstream inlet of the meter body. In a swirl meter, after the swirler there will be one Venturi section. On account of these two conditions vortices are produced properly. Also, on account of these inlet changes, the swirl meter give better accuracy in flow measurement, along with other advantages described in Section 3.0.5. The rest of the operation of the meter is the same as for a vortex meter. Another issue is that near the outlet side of the meter there will be a "deswirler" to eliminate "the tangential velocity imparted to the fluid at the inlet and avoids affecting operation of other downstream instrumentation" [18].

3.1.2 DESCRIPTION OF VORTEX METER

1. **Vortex meter:** Since the vortex frequency is proportional to velocity it is possible to get direct linear digital output from vortex meters without a converter and/or transmitter. Also, on account of its operation on a frequency basis, drift is not really applicable. Though it is possible to get direct digital output, in reality most of instruments currently available are equipped with some type of converters, etc. to make the meter smart and fieldbus compatible. Vortex meters are suitable for flow measurement in liquid, steam and gas in different sizes, starting from 15 mmNB up to 300 NB (below 15 NB it is not feasible). The minimum Reynolds number value, Re_{min}, defines the lower range value, i.e., the span decreases with increasing viscosity [1]. The vortex flow meter offers good accuracy of measurement over a wide flow range. However, it has limitations in the low flow range and requires long straight pipe length for it to operate accurately. Pulses per unit volume decrease as the meter size increases. *A meter size of 600 mmNB pipe with 3 m/s velocity would have a typical frequency of 5 Hz* [9]. A typical vortex meter is depicted in Fig. V/3.1.0-1 with different parts marked therein.

Vortex meters are *susceptible* to pipe vibration. Many modern meters, utilizing digital signal processing, have provisions for permanent built-in compensation for pipe vibration (e.g., prowirl 70 of Endress Hauser to protect pipe vibration up to 1 g and frequencies to 500 Hz). Since the meter does not have any moving parts, it is inherently less maintenance prone from a wear point of view. For main flow measurement there is no need for any valve manifold (like those in differential pressure transmitters), and hence there is easier installation with lower installation cost. However there could be an isolating valve for optional pressure sensors. The versions of the meter type mainly used in gas/steam flow measurements normally have a built-in temperature sensor and (optional) pressure sensor. The pressure-containing portion of the vortex flow meter is normally called the flow meter body. The flow meter body can be of two types, i.e., wafer/sandwich type and flanged end type. Low-cost wafer/sandwich design is installed between two side flanges attached to the pipe. The meters are available in remote versions where the sensor and converters are located separately. For better reliability there are meters with dual sensors. *This variant is ideally suited for measurements in multi-product pipelines, with two different products moved through one after the other (e.g., Optiswirl 4070 of Krohne). One signal converter can be programmed for one product, and the other signal converter for the other product* [19]. Major parts of the meters include the following.

- Meter body;
- Vortex shedder bar;
- Sensor(s);
- Temperature sensor (as applicable);
- Pressure sensor (as applicable);
- Optional isolating valve;
- Connection flanges (as applicable);
- Necessary gasket;
- Indicator (as applicable);
- Converter unit;

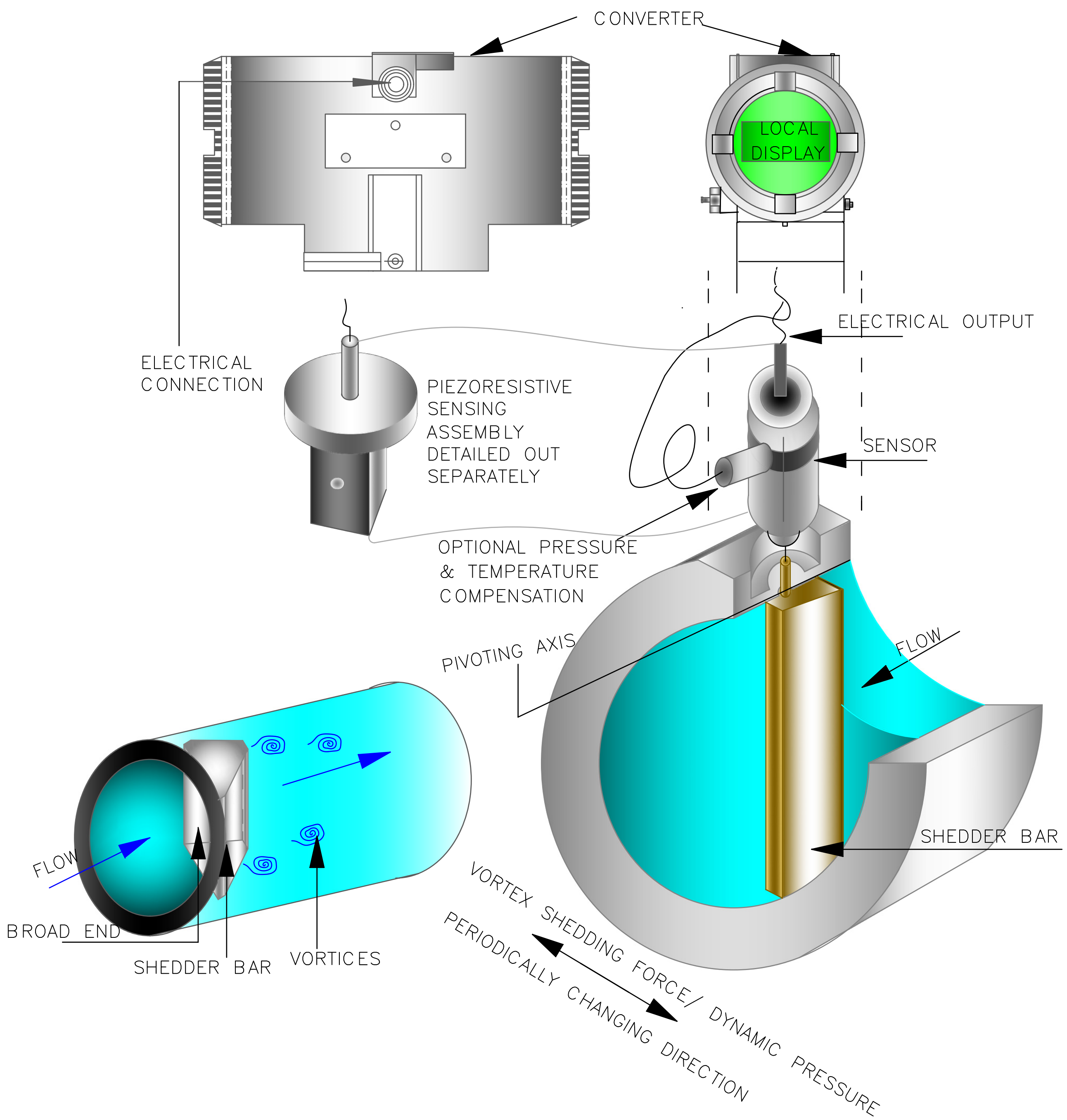


FIGURE V/3.1.0-1 Vortex meter.

- Lead wires;
- Cable connection(s);
- Accessories, such as mounting bracket, reducer.

2. **Swirl meter:** As stated earlier, from an operational point of view both vortex and swirl meters are the same, the main difference is the inlet flow conditioning for which swirl meters have lower susceptibility to flow profile, and hence less requirements for straight pipe length requirement and higher rangeability. The major parts of the swirl meter are the same as those discussed above. Additionally, swirl meters will have inlet a swirler, and

Venturi section. Also, it has a deswirler to eliminate downstream flow. Therefore, the additional components here are the swirler/deswirler and Venturi section. The remaining parts are similar to those of a vortex meter. On account of these it offers better turndown ratio.

3.1.3 BLUFF BODY AND SENSOR DESCRIPTION

In this section, short discussions are put forward to describe and establish general requirements for a bluff body and sensor. These are common to both vortex and swirl meters.

1. **Bluff body:** The shape and area ratio with respect to pipe dimension (internal diameter—ID) is very important because these parameters guide the manner in which vortices will be formed and the constancy of the Strouhal number. The optimum shape and size of the bluff body is determined empirically. An obstruction width (d) is one-quarter of the pipe diameter (ID) [9]. The bluff body should be chosen in such a manner that due to the bluff body, the geometry of the vortex formation should never change with the flow and that the Strouhal number remains constant over a wide Reynolds number range [1]. There are a number of shapes available for bluff bodies. Of the following types, the most popular has been depicted in Fig. V/3.1.3-1. Apart from the shapes/types listed below, other types are two part rectangular and two part delta [5].
   - Circular/cylindrical;
   - Rectangular;
   - Delta;
   - Tee bar.

   Various manufacturers claim additional advantages with the shape of bluff body chosen. However, the delta bluff body is seen in the majority of cases.
2. **Sensors:** During the discussions in Section 3.0.3, it was noted that vortex shedding on either side is a function of dynamic pressure. What does that mean? It means that when a vortex is shed in one side of the bluff body, the fluid velocity on that side increases, to keep the energy the same, and the pressure decreases. Exactly the opposite happens on the other side, i.e., that side will have lower velocity with increased pressure. This means that there will be differential pressure across the bluff body. In the next vortex shedding in

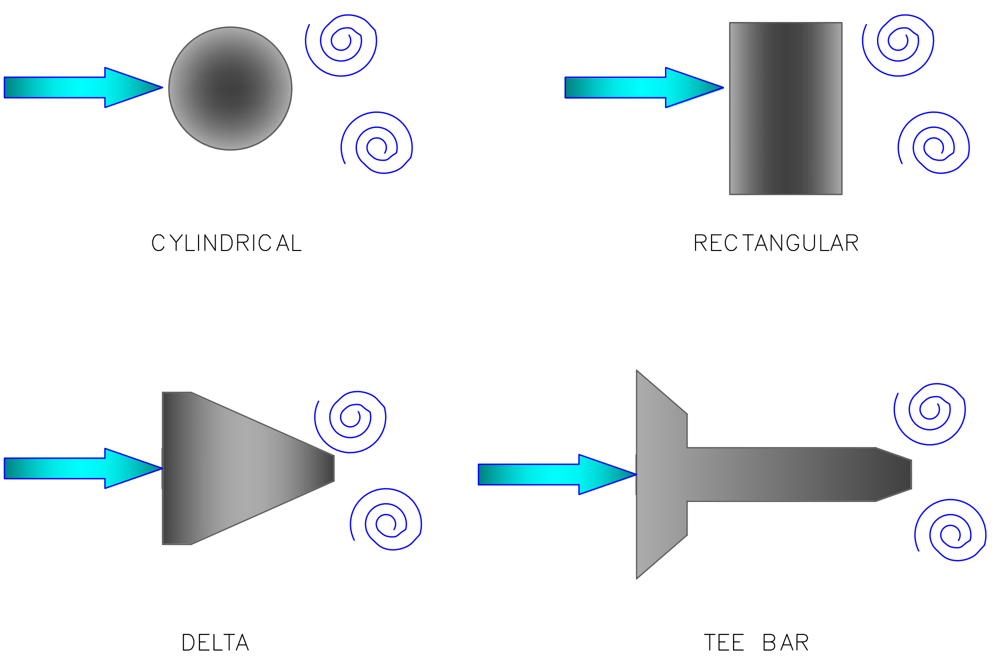


FIGURE V/3.1.3-1 Bluff body shapes.

the opposite side the same thing (velocity increases and pressure decreases) will happen to that side and consequently the reverse thing will happen to the other side. Thus dynamic pressure distribution adjacent to the bluff body would change to the same frequency as the shedding frequency. From the discussions it is clear that for detection there are a number of parameters available. Various detectors can be used to measure the following:

- Differential pressure across the bluff body sides;
- Oscillating flow/velocity across the face of the bluff body;
- A flow through a passage drilled through the bluff body [9];
- The oscillating velocity or pressure at the rear of the bluff body;
- Detection of free vortices present in the downstream to the bluff body.

When the question of measurement of pressure or differential pressure is the question, standard DP transmitter with, e.g., diaphragm based on piezoresistive sensing, or change of reluctance sensing, could be deployed. When measuring oscillating flow/velocity thermal sensor (e.g., Thermister), an inductive sensor (magnetic shuttle) could be selected. For the detection of free vortices downstream of the bluff body, changing the velocity component of the same could modulate the ultrasonic signal sent, and detecting the changes in traverse time flow can be computed. Thus one can conclude that there are a number of measuring technologies available for detection units/sensors. Thus sensors can be classified as:

- thermal;
- strain gauge;
- piezoelectric;
- capacitance;
- ultrasonic.

Mechanical detectors could be deployed but are rarely used in modern instrumentation. However, of all these methods, piezo-resistive sensors are most popularly used by manufacturers, such as ABB and Rosemount.

3.1.4 METER K FACTOR AND PERFORMANCE

In this section short discussions shall be presented on meter K factor and various other issues related to meter performance and typical performance values possible from available meters.

1. **K factor:** From Eq. (V/3.0.1-2), we get the expression for K factor of the meter. Also from Fig. V/3.0.2-1, it can be seen that there will be variation in the Strouhal number with Reynolds number. Therefore, there will be variation in the K factor with Reynolds number. Over a specified range of Reynolds numbers it is nearly constant and this specified Reynolds number range is referred to as linearity. Typical variations of meter K factor with Reynolds number are shown in Fig. V/3.1.4-1. It can be seen that the Reynolds number range theoretically is between 10,000 and 2,000,000 (for practical purposes it is between 150,000 and 2,000,000), which is linear.

   The wider the linear range a shedder exhibits the more suitable the device is as a flow meter [17]. Here one point to be noted is that the *shape* of the bluff body does not have much of an effect on low Reynolds number or linearity. Now as seen from the variation of linearity with Reynolds number, K factor varies sharply with Reynolds number beyond 15,000 in the lower range, therefore meter uncertainty will be high and hence degradation of meter performance and also specific gravity of the fluid is a deciding factor for lower range to get the necessary minimum acceptable frequency for measurement. On the maximum Reynolds number range two things happen, namely, linearity is degraded as well as there will be more pressure loss and it may give rise to cavitations. Brennan and Lomas, while investigating the bluff body shape, observed that K factor in *a vortex meter* remained unchanged for all liquids, gas, or in cryogenic applications.
2. **Performance (and limitation) discussions:** As a corollary to the above discussions one

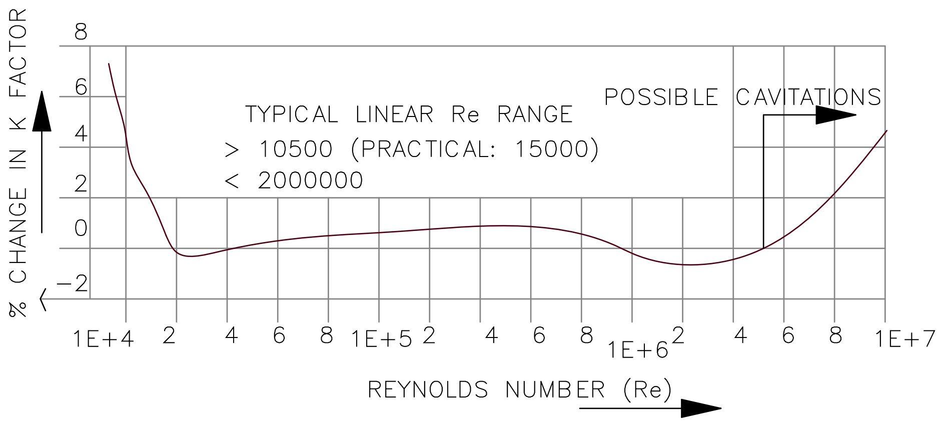


FIGURE V/3.1.4-1 Meter K factor.

would argue that the following various factors, which influence flow range and meter performance, are included at operating conditions:

- Fluid viscosity;
- Density;
- Vapor pressure;
- Meter pressure loss.

For low viscosity with moderate density, about 15–20:1 turndown ratio is possible when the velocity of the flowing fluid is sufficient (e.g., > 4 m/s). Pressure loss will be in the range of 27 kPa [9]. Low-pressure fluid (low density), especially for low-viscous fluids, will not be in a position to generate changes in dynamic pressure to measure. Similarly, high viscosity brings about the limit for the flow range, because vortex and swirl meters are not suitable for high-viscous fluids. Therefore, lower density and/or higher viscosity are two limiting factors for meter performance. Another issue applicable to both vortex meters as well as swirl meters is that they cannot measure ZERO flow as there is a minimum flow limit. Therefore both these meters are unsuitable for batch operation. Also, these meters cannot function if the flowing fluid tends to coat the bluff body. Presented below are a few performance data for these meters.

3. **Performance data for vortex meters:** The meter performance depends on many issues already discussed. Here some data have been presented to illustrate the meter performance available. The best possible data have been presented and may not be applicable for any single meter. As applicable, specific data for swirl meters have been indicated.
   - *Accuracy:* There may be variations in accuracy of the meter for liquid and gas flow. Normally, for liquid applications an accuracy of 0.65% AR to 0.75% is available for Re >20,000. The meter accuracy falls when the Reynolds number (Re) is less than 20,000 and in this range accuracy of 1%–2% AR possible. Similarly for gas applications, accuracy is 0.9% AR (higher Reynolds number) to 2% AR for lower Re. For swirl meters, an accuracy of 0.5% AR is common for gas and liquid applications.
   - *Repeatability:* Normally 0.2% AR to 0.1% AR is available for vortex, whereas for swirl meters it is 0.2% for >20 mmNB and 0.3% for smaller sizes.
   - *Velocity:* Most of the meter range can handle a wide range of liquid and gas velocities; some higher values are for gas velocity up to >90 m/s (namely, Emerson RM8800) and for liquid possible velocities 10 m/s, normal <5 m/s. For swirl meters gas velocity is in the range of 1.5–40 m/s and liquid velocity between 0.2 and 5 m/s. Normally the minimum measurable velocity (in m/s) is determined with the formula given by the manufacturer. This formula is a function of density ρ kg/m^3. Based on the design

against each model manufacturer provides one expression (one such *typical data and expression* is $\sqrt{\frac{54}{\rho}}$). Therefore, from the density at the operating condition it is necessary to compute the minimum velocity, then to check with the model number if that is within the meter model range or not, if not another model number may have to be tried. In connection with this, Subsection 3.1.5.6 may be referenced.

- *Turndown:* Possible turndown 30:1, however normal turndown ratio 20:1.
- *Stability:* Normally the meter is stable, however stability of 0.1%–0.01% per year is possible.
- *Temperature effect:* 0.05%/10 K

3.1.5 OPERATING PROCESS CONDITIONS

Short discussions on various operating process conditions have been presented below. One should keep in mind that efforts have been taken to indicate the maximum parameter in various meters available in the market. Naturally these data do not belong to any particular model but some assorted data from various reputed manufacturers.

1. **Process pressure:** Normally there are two versions of vortex available in the market, namely the normal and high-pressure versions. The pressure rating for the normal version may be around 30–35 bar, while for the high-pressure version it may be 250 bar (e.g., prowirl 70 of E + H). Normally swirl meters have a lower rating up to size 200 mmNB, these are for PN 10–40 and for size >200 mmNB it will be PN 10–16. Therefore, swirl meters normally have a lower rating, but on request up to ANSI 900 or PN 160 is possible in a swirl meter, e.g., Swirl master of ABB [20].
2. **Process temperature:** As in the case of pressure, there are two/three versions of a vortex meter. Available operating temperature range limits for various vortex and swirl meters are indicated below.

   Vortex meter: Normal: −29 to 280°C; high-temperature version: −29 to 450°C; lower-temperature version could be −55°C also. In cryogenic application the lower limit may be −200°C (e.g., YEL/Rosemount meters). For swirl meters: −55 to 280°C.
3. **Temperature–pressure derating:** It is important to note that most manufacturers provide the necessary curves to show how the meter pressure rating should be derated when used at different temperatures, i.e., there will be a pressure temperature curve from which one needs to select the pressure rating of the meter at the operating temperature. This has been clarified with an example in Fig. V/3.1.5-1.
4. **Process flange rating:** Normally meters are available with flanged type process connections. These flanges are usually supplied at international standards with associated pressure ratings (e.g., ANSI in pound class D in standard as PN number as already clarified in Fig. V/1.0.0-1). While specifying the meters, manufacturers provide a pressure–temperature curve for the various flange ratings. In order for the reader to understand the same, Fig. V/3.1.5-1 presents typical flange ratings of meters, given along with details on how to select the pressure and temperature for the application.
5. **Viscosity:** As stated earlier, the vortex meter is not suitable for high-viscous fluid. Also, viscosity value varies with meter size, with a typical normal viscosity of the meter up to 5 mPa·s for meter sizes up to 25 mmNB and above 25 mmNB it could be around 7.5 mPa·s, and in some cases up to 10 mPa·s. The swirl meter has the capability to handle higher-viscosity fluid, e.g., size up to 25 mmNB viscosity: 5–10 mPa·s; above 25 mmNB viscosity up to 30 mPa·s.
6. **Density:** There may not be any direct effects of density on meter performance, however,

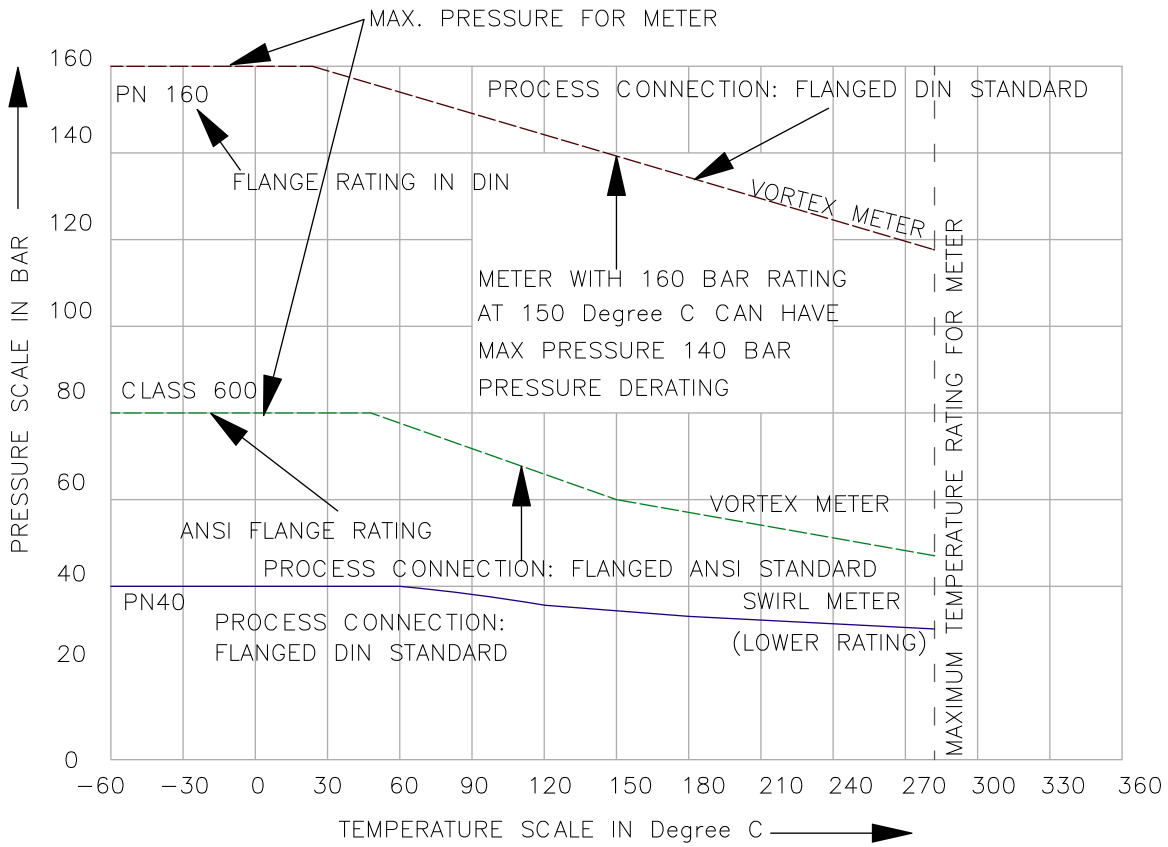


FIGURE V/3.1.5-1 Pressure temperature and process connection details. Left indented point 11 (1). The intent of this figure is to familiarize the reader on the following details for a meter, meter pressure ratings, meter temperature ratings, meter pressure derating with temperature, process connection and standards, flange pressure rating, (2) this is a generalized graphic representation from different reputed manufacturers, (3) this generalized graph is for understanding only and not for any meter designing.

as every meter has a minimum velocity to handle, density limits may come from that, as already discussed in Subsection 3.1.4.3. Therefore, for sizing, density should be taken into account. Also, one should note that the measurement of low-density gas flows in a vortex meter is problematic as vortices would not have a strong enough pressure pulse. Low-density gases can be measured with a vortex meter if the minimum measurable flow corresponds to a high fluid velocity [5].

7. **Reynolds number:** There is a distinct difference in lower Reynolds number handling capabilities of vortex and swirl meters. This is natural, because of the swirl meter inlet swirler and Venturi section. As already discussed for vortex meters, the minimum and maximum Reynolds number limits should be 11,000−160,000. When high pressure is available to avoid cavitations, a higher Reynolds number may be possible. In contrast, in the swirl meter, keeping the higher Reynolds number range the same, the lower range of Reynolds number can start from only 2100.
8. **Pressure loss and cavitations:** Pressure loss in the vortex meter is not that high. However, a major issue here is that the pressure loss in the meter should never be a cause of cavitations, especially for liquids with lower vapor pressure. It is a known fact that cavitations cause damage to pipe. Cavitation can adversely affect meter accuracy and may directly damage the meter, therefore this is very important. Pressure loss in a meter is function of flow/velocity through the meter and density at the operating condition.

Therefore pressure loss can be obtained from the following equations.

$$\Delta p = A \cdot \rho_{op} \cdot \frac{q^2}{D^4} \qquad (V/3.1.5\text{-}1)$$

where ΔP: pressure loss (kPa); ρ_{op}: density at operating condition (kg/m^3); q: flow in m^3/h. A (A′ for the second equation) is a constant based on meter style, fluid type (liquid/gas), and flow unit. Normally manufacturers specify these values. Similarly, if the velocity is known the pressure loss can be calculated as

$$\Delta p = A' \cdot \rho_{op} v^2 \qquad (V/3.1.5\text{-}2)$$

From any of the above equations pressure loss can be calculated. The above equation is valid for a meter size equal to pipe size. However, if there is a reducer used then pressure loss will be a certain percentage (indicated by the manufacturer as, e.g., 15%/20% more) higher than the standard size. In order to avoid cavitations, it is necessary to ensure that due to net pressure loss (standard pressure loss and pressure loss due to the reducer) it never falls below the vapor pressure of the flowing liquid. Therefore, from the net pressure loss calculated above, it is necessary to ensure that pressure at 5D (pipe internal diameter), downstream of the meter is more than or equal to pressure calculated as per the following equation to eliminate cavitations:

$$P = 2.7 \times \Delta p + 1.3 P_v \qquad (V/3.1.5\text{-}3)$$

where P = pressure in kPa (abs) at 5D downstream of meter; P_v = liquid vapor pressure in kPa (abs).

9. **Pipe vibration process noise:** When there is vibration in the pipe there is the possibility of error in meter readings. However, in most modern instruments currently available necessary compensations are provided in the meter to take care of vibration to a certain extent. The actual limits of pipe vibration are a function of pipe size and measurement range. The typical acceleration value is restricted to 1 g (up to 500 Hz) as per standard IEC 60068-2-6 [20]. Similarly, other process noises may be the cause of false readings of the meter. In the case of liquid measurement on account of the high signal-to-noise ratio of the sensor, this problem may not be prominent. For gas/steam flow on account of weak signal from the sensor, the problem may be acute. The best way to eliminate this is by using a suitable filter circuit in the electronic measuring circuit by estimating the situation before installation.

3.1.6 ENVIRONMENTAL CONDITIONS AND PROTECTIONS

1. **Environmental conditions:** Temperature withstand capability of the meter varies with the manufacturer. Meters are available in normal and high-temperature versions (may not be applicable for swirl meters). Not only is process temperature considered for selection of the high-temperature version but ambient temperature also plays a role. If the ambient temperature is high then for certain cases high-temperature versions may have to be chosen. Therefore, ambient temperature is established as a function of process temperature in model selection [21]. Typical ambient conditions for meters are as follows:
   - *Storage temperature:* −50 to 85°C;
   - *Ambient temperature during operation:* −29 to 75°C;
   - *Relative humidity:* Normal 85%; climate proof design: 100%.
2. **Protection:** Normally meters have the necessary protection and protection certificates such as the following:
   - *Enclosure:* NEMA 4X/IP 66/67;
   - *Explosion-proof:* Ex-d, Ex nA—see Ref. [22] for further details;
   - *Intrinsic safety:* Ex ia—see Ref. [22] for further details.

Now with some idea about the meter from the descriptive details of the meter, it is time to see the features of the meter type and the application areas.

3.2.0 Features and Applications of Vortex/Swirl Meters

Vortex/swirl meters are one of the modern meters normally deployed in industries and plants for flow measurements. In this section the meter types and application areas will be highlighted. Both types are discussed together here.

3.2.1 VORTEX/SWIRL METER FEATURES

There are a number of features associated with these meters to make them unique amongst the other fluid flow measurement meters. Features of these meters are categorized here as advantages and disadvantages.

1. **Advantages:** The following are the major advantages of vortex/swirl meters:
   - Proven but comparatively modern flow-measuring technology;
   - High-accuracy flow measurement liquid/steam and gas;
   - Possible flow measurement of conductive and nonconductive fluid;
   - Normally insensible to relative position of flow meter;
   - Insensible for higher loads;
   - Possible to cover wide pressure and temperature ranges;
   - Integrated gross and net heat calculation for steam and hot water;
   - No moving parts, hence less wear;
   - Advanced sensing technology;
   - Advanced digital signal processing (DSP) technology;
   - With DSP possible to analyze flow conditions;
   - Initiation of automatic optimum adjustments;
   - Self-diagnostics;
   - Simple parameter setting;
   - Smart versions in HART/fieldbus available;
   - Comprehensive communication options;
   - Automated zero point adjustment for swirl meter;
   - For safe operation, meter could be developed as per IEC 61508 edition 2;
   - Available with built-in pressure and temperature compensation for mass computing, e.g., 602VFM Multivariable VORTEX mass flow meter of Spire Metering Technology LLC or AX2000 series of Azbil Corporation.
2. **Disadvantages:** There a few characteristic disadvantages of these meter types as listed here.
   - Vortex and swirl meters are unsuitable for high-viscosity fluids;
   - Zero flow cannot be measured by vortex/swirl meters;
   - Not suitable for batches and many other control applications;
   - Not suitable for low-density fluid with lower velocity;
   - Operation possible only in a band of Reynolds number (for swirl meters this band is wider in the lower side).

3.2.2 APPLICATION AREA

The application area of the flow meter widens with time. The major such areas include but are not limited to the following applications:

1. Measurement of saturated steam and superheated steam;
2. Boiler performance monitoring in various industrial applications;
3. Steam flow, feed flow, and condensate flow applications in utility plants;
4. Heat metering of chilled water, hot water, and steam in HVAC;
5. Measurement of consumption of industrial gases and air;
6. Compressed air systems;
7. Performance monitoring of compressor;
8. Free air delivery (FAD) [23];
9. SIP and CIP processes in the food, beverage, and pharmaceutical industries [23];
10. Many safety-related applications;
11. These meters find their application in all major industries. Some of these are:
    - utility/power plants;
    - chemical plants;
    - oil and gas;
    - pharmaceuticals;

- food and beverages;
- metallurgical plants;
- paper and pulp;
- water treatment;
- automobile industry.

3.3.0 Design Aspects of Vortex and Swirl Flow Meters

There are a number of design issues related to the meter types in question. In the following discussions some of these design issues shall be addressed. The discussions start with the most sensitive and important component of the meter types, i.e., the sensor.

3.3.1 SENSOR AND CONVERTER DESIGN

From the above discussions it is clear that in these types of meters, vortices are generated and such vortices would generate periodic variations in dynamic pressure velocity. Therefore, there are various methods of vortex determination. Earlier sensors were nonwetted types and were highly sensitive to plugging and required frequent maintenance [9]. Also, these were very sensitive to pipeline vibrations that produced false signals. There has been a lot of modification in the design. In this section various sensor design types will be discussed. Of various sensor designs for vortex meter, the piezoresistive design is the most popular and this sensor design is used in swirl meters also.

1. **Piezoresistive sensors:** In the case of piezoresistive design, a piezoelectric crystal is encapsulated by a double-faced diaphragm filled with liquid. Piezoelectricity and piezoelectric phenomenon have described in Fig V/6.1.4-1 for better understanding of the phenomenon. The alternating vortices shed on each side of the shedder, i.e., the dynamic pressure changes produced by the vortices act on two diaphragms mounted on each side of the sensor. Such pressure changes are transmitted to the sensor through the filling liquid. Thus the flexing motion is transmitted to the piezoelectric sensor, which is located outside the flow line. Upon sensing the dynamic pressure changes, the sensor converts them to an alternative electrical signal from which, through the preamplifier and transmitter/converter, pulse/analog output is produced. This type of sensor, along with a transmitter, is depicted in Fig. V/3.1.0-1 with the sensor assembly shown separately. This type is also used in swirl meters by ABB.
2. **Capacitive sensors:** Capacitive sensors are also used by many manufacturers (e.g., prowirl 70 of E + H). In this type of design, basically differential capacitance is measured with the help of a suitable oscillator circuit. Within the assembly there is one fixed plate/electrode with ports in the fixed plate. The entire assembly is filled with suitable liquid acting as a dielectric and the assembly is sealed. The oil being incompressible fluid fully supports the diaphragms against high static pressure. On account of vortex shedding there will be changes in the dynamic pressure alternately on two sides of the bluff body. So, at any point in time, there will be an asymmetric differential pressure, when vortex shedding occurs. Therefore, the diaphragms deflect and the oil transfers through the internal port from one side to the other as shown in Fig. V/3.3.1-1A, to displace the other (variable) plate also.

   As the diaphragms deflect there is a change in the capacitance between the fixed plate and diaphragms (variable plates). On one side capacitance increases (e.g., C+) and on the other side it decreases (e.g., C−). For plate-type capacitance, the capacitance values are inversely proportional to the distance between the plates, and the changes in dynamic pressure are used to vary the plate distance, i.e., the capacitance value. This is somewhat similar to the capacitance type DP transmitter. According to the manufacturers these types of sensors give good resistance for pipe vibration effects and can be used for high temperatures (>400°C).
3. **Strain gage sensors:** When the vortices are created due to passage of flow by the bluff

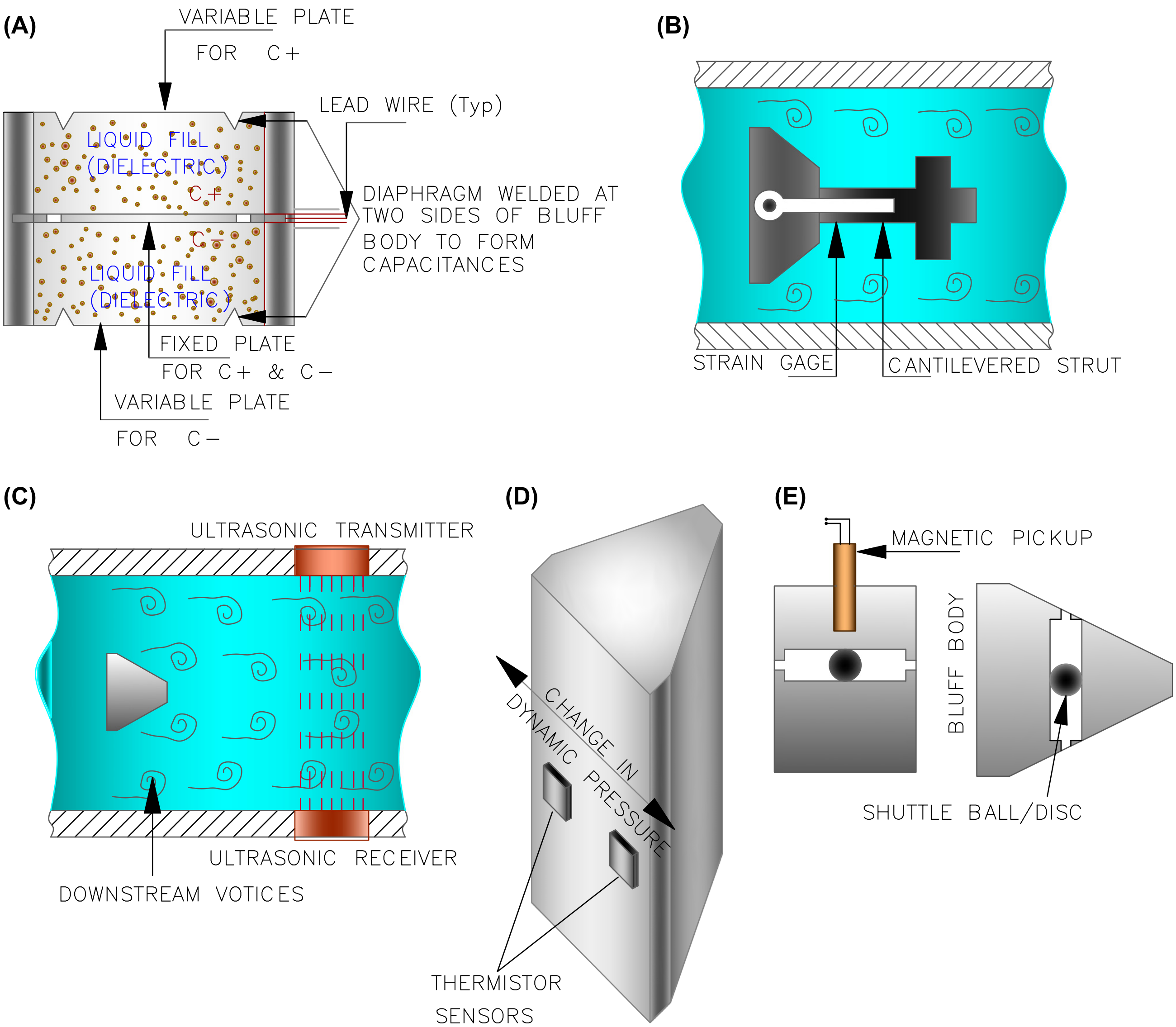


FIGURE V/3.3.1-1 Sensor design. (A) Capacitive sensor. (B) Strain gage sensor. (C) Ultrasonic sensing. (D) Thermistor sensor. (E) Magnetic sensor. Note: For peizoresistive sensors refer to Fig. V/3.1.0-1.

body, then it causes a slight displacement of the bluff body. This displacement of the bluff body is related to the flow. The body displacement is of the order of 10 μm [5]. This elastic movement is measured/detected by a cantilevered strut, as shown in Fig. V/3.3.1-1B, to which strain gauges are attached. Therefore, on account of bluff body displacement the stain gage will be subject to mechanical strain to cause a change in the resistance of the strain gauges. With the help of a standard bridge circuit the change in resistance is measured. The major drawbacks of the design include lower operating temperature (higher temperatures may cause an error in reading of the actual flow) and susceptibility to pipe vibration.

4. **Ultrasonic sensors:** As the name suggests in this design an ultrasonic transmitter and receiver are used and mounted at the downstream of the bluff body as shown in Fig. V/3.3.1-1C. Here the velocity components in the free vortices downstream of the bluff body are used to modulate an ultrasonic beam, sent by the transmitter for the ultrasonic receiver

placed diametrically opposite side of pipe. On account of free vortices at the downstream of the bluff body, the ultrasonic beam will be modulated, so, the resultant output will be the vortex signal. This sensor design is insensitive to pipe vibration and offers a good turndown ratio. The main drawback is that extraneous sound sources can affect measurements.

5. **Thermistor sensors:** A thermistor is a heat-sensitive semiconductor resistor or a thermal sensor with a high temperature coefficient (i.e., change in resistance per degree change in temperature). The temperature coefficient of a thermistor can be positive or negative. Response time of thermistor is quite good. For these reasons, thermistors are chosen as sensing elements. Each side of the thermistor is heated with a constant current. On account of vortex shedding there will be changes in velocity on either side of the bluff body. Therefore, due to fluid velocity, heat from the preheated thermistor element is taken away by convection from the fluid. Also, this phenomenon can occur between two thermistor elements (based on which side vortex shedding is taking place). This will result in a change in resistance. Such changes in resistance are measured in the bridge circuit to generate the pulse output. Normally two sets of thermistors are placed at the front side (sidewise) of the bluff body as shown in Fig. 3.3.1-1D. Thermistors are sensitive to dirt and are generally incapable of withstanding temperature shocks [5]. This type of sensor is not suitable for high frequencies, so they are not used in small meters, especially for gas applications.
6. **Magnetic type sensing:** This type of sensing is not currently very popular. Magnetic pickup is also commonly known as a shuttle ball/disc sensor. A ball or disc made up of magnetic material (e.g., nickel) is placed in a slot within the bluff body. The slot is connected at the sides by ports. Under the influence of the vortices (due to changes in periodic dynamic pressure), the ball/disc moves along a lateral slot connected by ports at both sides of the bluff body, as shown in Fig. V/3.3.1-1E. The movement of the ball/disc is detected by a magnetic pickup which through a preamplifier generates a pulse output. As mentioned earlier this method is not popular because there is a chance of the port opening becoming blocked by dirt and/or slowing down due to steam condensation from saturated steam.
7. **Converter types and style:** Vortex and swirl meters have necessary preamplifier and converters. In this regard there are several versions available. Most are describe here:
   - *Single variable with integral converter:* This unit measures only flow with the necessary converter integrated with the unit;
   - *Flow meter with built-in temperature compensation:* used for measuring of liquids, gases, and vapors. This unit has a built-in temperature compensation unit for saturated steam. The converter is an integral unit;
   - *Multivariable with integrated converter:* This measures not only flow but also pressure and temperature. The integral converter also has provisions for built-in pressure and temperature compensation units. These types can be used for gas/wet gas/steam flow measurements. Also, direct mass flow is measurable. In some cases the isolating valve for pressure changes during operation (OPTISWIRL 4070 of Krohne);
   - *Dual/double-sensor design:* There are versions where dual sensors are used. These are a redundant design with two sets of sensors and converters. They are very effective in eliminating noise. The converters are an integral part of the meter. In the case of a swirl meter of ABB, dual versions are available in remote types;
   - *Remote version:* In the case of remote versions, converters can be located away from the main unit. Also, these remote versions are available in field housing types. The distance between the meter and converter could be up to 30 m. Most of the

types discussed above as integral versions are available as remote versions also.

8. **Smart converter discussions:** While selecting the sensor and version of the meter, people are looking for a modular version, with easy replacement facilities. Currently, most meter designs are available as smart versions to support HART protocol, and advanced communications through fieldbuses, such as Profibus and foundation fieldbus. Details regarding smart instrumentation and associated communication systems have been covered in Chapter XI in a consolidated manner. For safety fieldbus system, Ref. [22] may be consulted.

3.3.2 BLUFF BODY DESIGN

Normally flows have three types of instability, namely boundary layer instability, separated shear instability, and Karman vortex instability. In aerospace applications many shapes are applicable but in vortex meters a sharp edge in the bluff body is preferred and used to:

- remove changes in boundary layer;
- improve accuracy;
- bring about regularity and stability.

Two major considerations for the bluff body are the shape and area ratio in the pipe. These factors define the manner of vortex shedding and the constancy of the Strouhal number [1]. A good vortex meter for flow measurement should have very *strong* vortex intensity with *low* permanent pressure loss. It is observed that blunt-shaped bodies are generally good vortex shedders, though they result in significant energy losses. The coefficient of drag and permanent pressure loss (PPL) in cylindrical shapes is minimal [24]. Also, the drag coefficient can be reduced using a split in the bluff body or use of end plates. However, on account of low-energy vortices, blunt shapes are not the preferred option for vortex meters. Therefore, sharp-edged bluff bodies generate better (stronger) vortex shedding than circular/cylindrical ones. Vortex meter sharp-edged bluff bodies are described in Fig. V/3.1.3-1. Again, out of various sharp-edged bluff body types, trapezoid or popularly known as delta shapes are reported to be strong and stable vortex generators. The ratio of bluff body width and pipe internal diameter (D) plays a great role. In this connection two observations shown in Fig. V/3.3.2-1B (developed based on an idea from [25]) may be referenced. Here two observations are important, at w/D nearly 0.35 K factor is minimal, which ensures that a small variation in w/D will have a minimum effect on frequency. Also, oscillating lift coefficient is nearly at its highest. After observing the wake parameters of the bluff bodies it has been seen that the Strouhal number, vortex formation length, and the wake width are dependent on each other [26]. The wake width is found to have an opposite behavior to that of the vortex formation length. The wake width determines the degree of shear layer interaction, and hence the Strouhal number. So, as stated earlier bluff body width at 1/4 to 1/3 pipe ID is the typical value normally chosen. The major reasons behind this (as suggested by Zankar and Cousin) are [25] listed here:

- Coherent shedding (vortex shedding from end to end of the bluff body on the same side at the same time) in a shorter length of bluff body between the end pipe walls;
- Accelerating flow through the smaller space between the bluff body and pipe walls, leading to uniform flow with less dependence on upstream profile.

If w/D is more then it may not be possible to get stable coherent vortex shedding.

At this time it is important to define various parameters of bluff body with the help of a suitable illustration as shown in Fig. V/3.3.2-1A.

Width is the dimension in which the flow is facing, designated as w. Total depth as shown is designated by H and length is defined as the height of the bluff body. The length and width ratio is another important issue. If the length is too long, i.e., it is a slender bluff body, then the vortex shedding will not be coherent and weak vortices will be produced. So, optimum L/w to be chosen so that the vortices will be strong

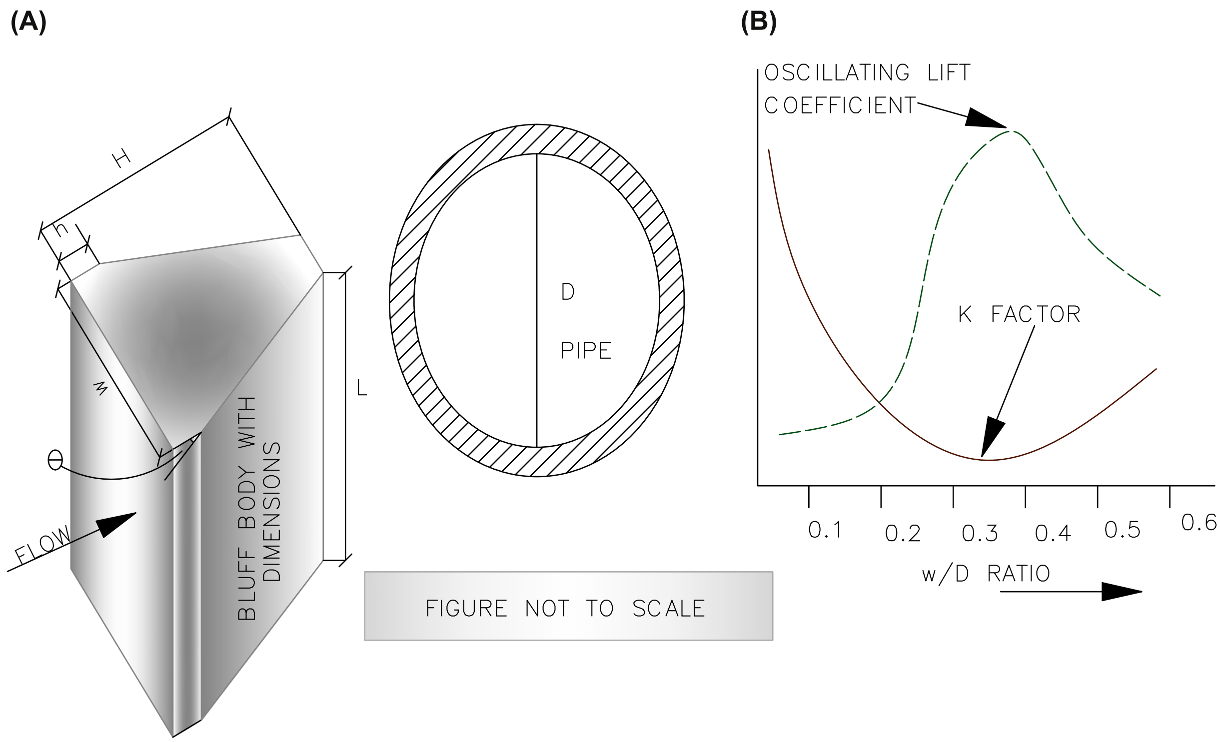


FIGURE V/3.3.2-1 Bluff body design. (A) Bluff body dimensions. (B) w/D and meter performance. *This figure is developed based on an idea from R.C. Baker, Flow Measurement Handbook, second ed., Cambridge University Press, 2000.*

and coherent. These discussions conclude with reference to Table V/3.3.1-1 where the observations of Takamoto and Terao about the effect on K factor and measurement error for selected parameters of the bluff body have been presented so that the designer can have a feel for the necessity and importance of wake parameters/bluff body parameters as indicated in Fig. V/3.3.2-1A.

3.3.3 FLOW RANGE AND SIZING

The nominal diameter is selected on the basis of the maximum operating flow and this should not be less than half the maximum flow rate for each nominal diameter. The linear lower-range limit value is dependent upon the Reynolds number. Therefore, viscosity and density (specific gravity) should be taken into consideration

TABLE V/3.3.1-1 Bluff Body Parameter Selection (see Fig. V/3.3.1-1A for Dimensions)

Dimensions	Selected Values	Measurement Error	Effect on K Factor (%)
w/D	0.28	0.1%	0.13
H/D	0.35	0.7%	0.09
L/D	0.912	0.15%	0.08
h/D	0.03	6.6%	0.13
θ	19 degrees	0.4 degrees	0.05

while making the sizing of the meter because they affect the lower limit. As stated earlier, the upper range is limited by pressure loss mainly so as to avoid cavitations in the case of liquid flow measurement. Some flow ranges of reputed manufacturers have been given to enable the reader to get an idea of the flow range specification and associated parameters. Two separate tables Table V/3.3.3-1 & Table V/3.3.3-2 are provided for the vortex meter and swirl meter. In these tables the reader should take note of sharp changes in maximum flow and frequency between liquid and steam and gas for the same sizes. Also, the reader should take note of differences in flow, Re_{min} (for liquid), and frequency between vortex meters and swirl meters.

TABLE V/3.3.3-1 Flow Range for Vortex Meter

Pipe	Size DN mm (Inch)	15 (1/2)	25 (1)	50 (2)	100 (4)	200 (8)	300 (12)
For Liquid Applications							
DIN	Max flow m^3/h	6	18	70	270	1100	2400
DIN	Re_{min}	10,000	20,000	20,000	33,000	120,000	155,000
DIN	Frequency (Hz)	370	240	180	100	50	26
ANSI	Max flow m^3/h	5.5	18	66	216	935	2040
ANSI	Re_{min}	11,000	23,000	22,000	44,000	128,000	157,000
ANSI	Frequency (Hz)	450	400	176	75	40	23
For Steam/Gas Applications							
DIN	Max flow m^3/h	24	150	500	1900	8000	20,000
DIN	Re_{min}	10,000	20,000	20,000	33,000	120,000	155,000
DIN	Frequency (Hz)	1520	2040	1200	700	285	217
ANSI	Max flow m^3/h	13	48	265	1059	4002	10,006
ANSI	Re_{min}	11,000	23,000	22,000	44,000	128,000	157,000
ANSI	Frequency (Hz)	1980	1850	1180	635	240	195

Based on Data from ABB. Courtesy: ABB.

TABLE V/3.3.3-2 Flow Range for Swirl Meter

Size DN mm (Inch)	15 (1/2)	25 (1)	50 (2)	100 (4)	200 (8)	300 (12)	400 (16)
For Liquid Applications							
Max flow m^3/h	1.6	6	25	150	500	1000	1800
Re_{min}	2100	5200	17,300	17,500	44,000	115,000	160,000
Frequency (Hz)	185	135	90	77	30	16	13
Steam/Gas							
Min flow m^3/h	2.5	5	18	65	200	530	1050
Max flow m^3/h	9.4	29	206	882	2880	5880	11,770
Frequency (Hz)	1900	1200	1200	700	320	160	150

Based on Data from ABB. Courtesy: ABB.

Note the base conditions considered for specifying flow rate in the following tables.

Liquid—density: 998 kg/m^3; pressure: 1.013 mBar; temperature: 20°C; viscosity: 1 cSt.

Steam/gas—density: 1.2 kg/m^3 Suitable flow conversion in STP is necessary. In the table only selected meter sizes have been given. *The designer is advised to refer to the actual data of the manufacturer for the particular application.*

Most of these meters are available with some overload capabilities. Usually manufacturers specify them in their product catalogs.

3.3.4 MATERIALS OF CONSTRUCTION

Like any other flow meter in process applications the materials of construction for various components are of great importance. Oxygen application is one critical issue. This applies not only to this meter but to all other meters also. In many cases special treatment may be called for. Also, because of the nature of the oxygen reaction it is recommended to use nonferrous materials. Here some commonly used materials for various components of vortex/swirl meters have been specified in Table V/3.3.4-1, based on data from a few reputed manufacturers.

3.3.5 METER MOUNTING STYLE

Vortex/swirl meters are available in two versions. These are the flanged and wafer versions. In many cases, especially to combat low-flow measurements, meters are chosen a size lower than the pipe size. In such cases reducers are used. For that, as well as for remote converter types, either of these two versions is used.

Flanged version: In this version, at the two sides of the meter there will be two flanges of suitable material, pressure rating, and standards. These will be fitted with a companion flange in the piping work.

Wafer version: The wafer version of the meter is fitted between the two pipe flanges.

We now look at the meter specification details.

TABLE V/3.3.4-1 Materials of Construction of Vortex/Swirl Meter Components

Component	Materials Normally Available From Manufacturers
Housing	Aluminum alloy (Lo copper), SS 1.4571[a] (316Ti[b]/316L) Hastelloy CF8[c], CF8C
Flange (Non wetted)	316 SS/CS
Flange (Wetted)	316/316LSS, nickel alloy, A105 forged carbon steel LF2 forged carbon steel, wrought duplex stainless steel
Meter Body	CF-3M cast stainless, N06022 wrought nickel alloy and CW2M cast nickel alloy, ASTM CF8M
Shedder Bar	ASTM S31803 (15NB); >15NB: EN 1.4517 or AISI 316Ti, SS 1.4671,AISI 316L Hastelloy
Swirl Body	SS 1.4571 (316Ti/316L) Hastelloy CF8, CF8C
Sensor	AISI 316Ti, SS 1.4671,AISI 316L Hasalloy, SS 1.4571
Gasket	PTFE, Graphite, Kalrez 6375 etc. Depending on temperature
Collars	Nickel alloy N06022, 316/316L stainless steel
Measuring sensor	SS 1.4404/316L
Measuring tube gasket	SS 1.4435/316L

[a]*Euro norm of specification (typical).*
[b]*ANSI norm of specification (typical).*
[c]*Alloy casting (ASTM) (typical).*

3.4.0 Specification for Vortex and Swirl Meters

The specification for vortex/swirl meters has been detailed in Table V/3.4.0-1. Specific requirements for swirl meters have been indicated separately.

(Maximum available values for different meters are given here and may differ from any particular model—the designer must specify data pertinent to the application.)

TABLE V/3.4.0-1 Specification of Vortex/Swirl Meter (*Inline Type*)

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Liquid/steam/gas (say)*		*To specify fluid. Liquid and gas meters are separate meter range Re_{min} number etc.
2	Design pressure	250 bar (max) special cases		
3	Design temperature	(−)29−280°C even 450°C for high temperature version		
4	Derating	Pressure value is dependent on temperature so suitable derating to be done Ref: Fig. V/3.1.5-1		
5	Viscosity	Normally 0−10 mPa·s extreme case 30 mPa·s also possible		
6	Environmental condition	Refer Section 3.1.6		
7	Pick up type	Piezoelectric, capacitance, strain gage, thermistor, magnetic/mechanical		
8	Output	Pulse (varying frequency range, e.g., 20−2500)/ 4−20 mADC Smart version with HART protocol, Fieldbus communication systems available		
9	Output function	Electronic totalizer, remote transmission, pressure temperature compensation even other control function, e.g., boiler feed flow control		
10	Materials of construction	Refer to Section 3.3.4		
11	Enclosure class	NEMA 4X/IP 66/67		
12	Electronics unit	ABS, Epoxy encapsulated		
Connection and Mounting Details				
13	Process	Flange Din/ANSI standard pressure rating matching application PN 250/ANSI 900 class possible		
14	Electrical	½″NPT/ET ISO M20 or manufacturer standard		

Continued

TABLE V/3.4.0-1 Specification of Vortex/Swirl Meter (*Inline Type*)—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
15	Mounting	Horizontal/vertical		
16	Temperature and pressure compensation	Where required to be provided, normally downstream side tapping 3−5D for pressure, 2−3D for temperature		
Performance and Other Details				
17	K factor	Refer to Section 3.1.4		
18	Accuracy	Refer to Section 3.1.4		
19	Repeatability	Refer to Section 3.1.4		
20	Certification	Necessary certification from appropriate authority for hazardous application		
21	Application	Liquid/gas/steam in various industries		
22	Accessories	Rate flow and totalizing indicator, transmitter, communication facility		
23	Converter	To convert preamplifier signal to required output		
24	Hazardous application	Suitable certification from a competent authorities		
25	Special feature	If any to specify requirement		

3.5.0 Mounting and Installation of Meters

In this section short discussions on the mounting and installation requirements of vortex and swirl meters are covered. The discussion starts with mounting of the meter.

3.5.1 MOUNTING OF VORTEX/SWIRL METERS

As discussed earlier that there are mainly two versions of inline vortex and swirl meters available. In addition, the insertion type vortex meter is also available. One common requirement prior to installation of the meter is that it is necessary to ensure that the mounting/installation follows strictly *flow direction*. Inline meter types include the following:

1. **Wafer version:** The wafer version is mounted in the pipeline between the two pipe flanges as shown in Fig. V/3.5.0-1A. As also discussed earlier there are two possible types, i.e., the integral converter and the remote converter, which can be mounted in the room/field locations also (if the field-mounted version is opted for), around 30 m away.
2. **Flanged version:** This is the same as that described above, with the only difference being that it has a built-in flange of suitable pressure and temperature rating as per international standards, such as DIN/ANSI, BS, etc. The pipe mounting of the meter is done with the help of pipe companion flanges. Exactly like the wafer version, integral and remote converters are also available (refer to Fig. V/3.5.0-1A).
3. **Insertion type:** The insertion vortex meter can be directly mounted in the pipeline without

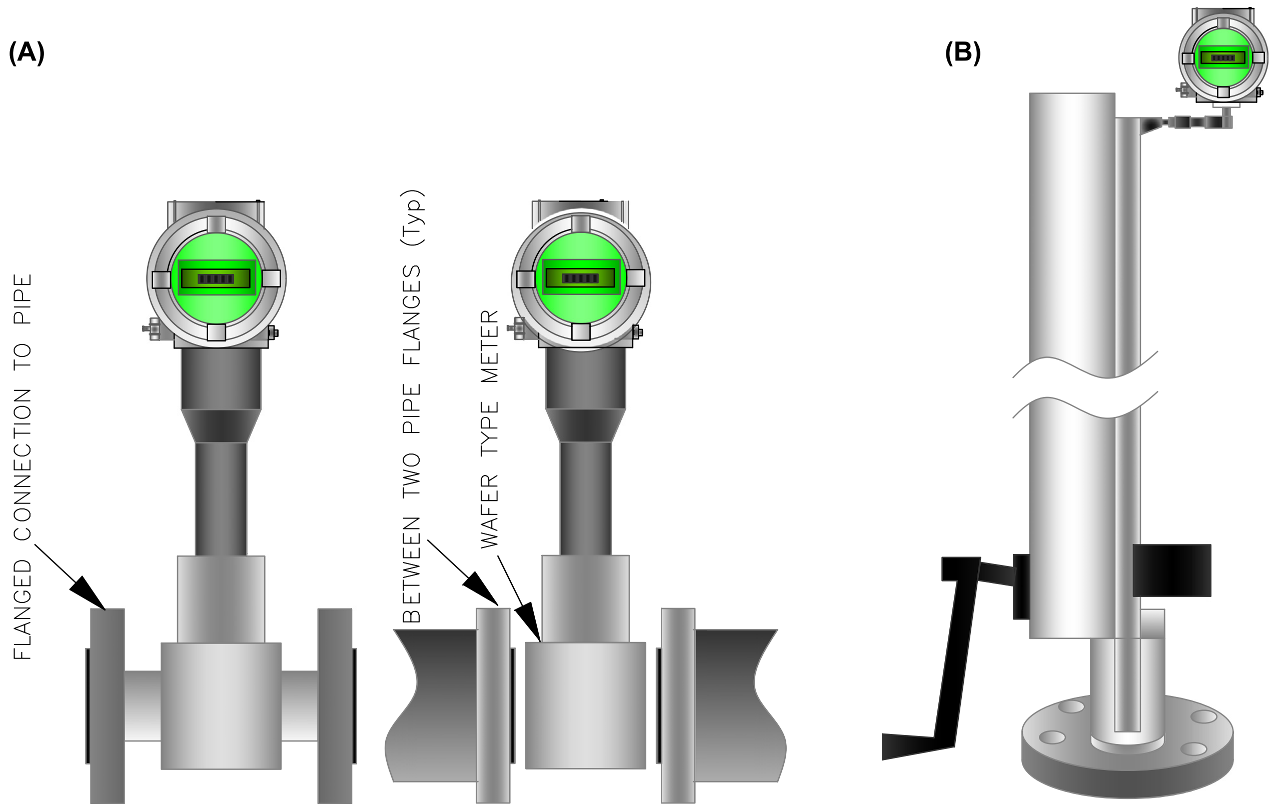


FIGURE V/3.5.0-1 Vortex swirl meter mounting types. (A) Inline meter types. (B) Insertion type meter.

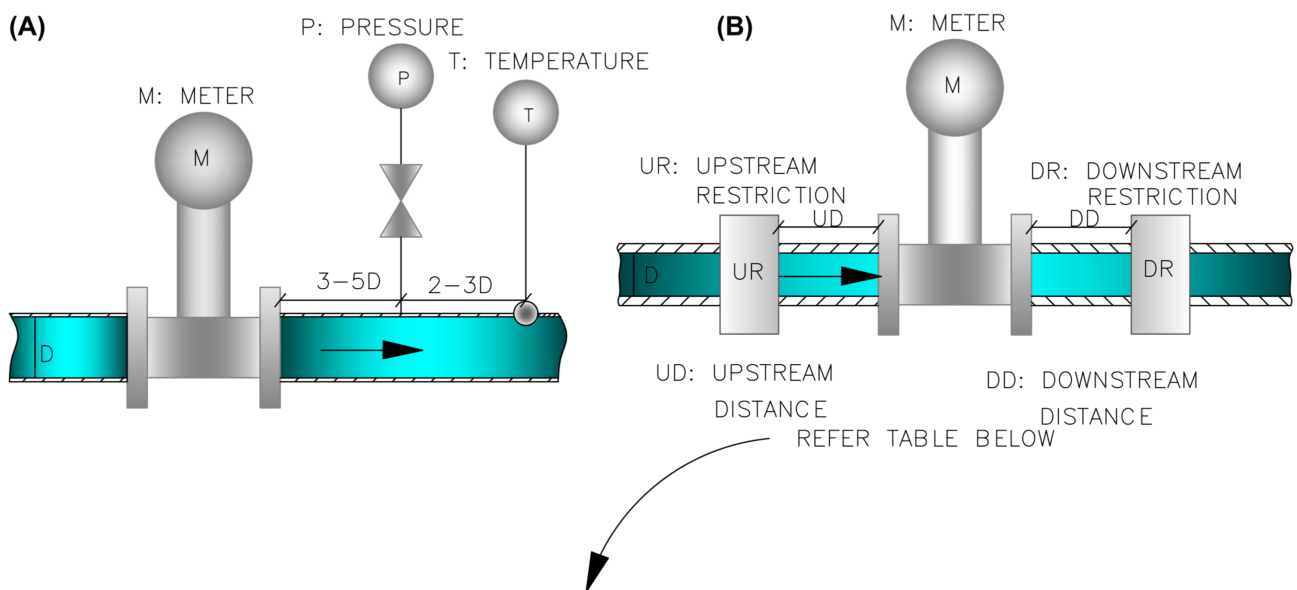
disturbing the flow. There will be a mechanism to control the insertion length. The insertion type vortex meter is discussed in the next section. The meter can be mounted from the top of the pipe through a suitable mounting pipe tapping of required size.

Now it is time to see the basic requirements for vortex and swirl meter installations.

3.5.2 METER INSTALLATION DISCUSSIONS

In this section, short discussions are presented on various installation procedures and pipe straight length requirements for various kinds of restrictions in upstream and downstream sides. From the earlier discussions it is clear that the vortex meter requires a fully developed flow profile. Naturally, to meeting good approach requirements, straight length requirement restrictions are placed on the installation of the meter. The straight length not only depends on the upstream restriction type but also to a certain extent on the design of the meter. For this reason there may be variations in straight length requirements between meter types. Compared to the vortex meter such requirements are less in the case of a swirl meter, on account of the built-in swirler Venturi design. The discussions shall be in three parts: basic installation requirements, tapping points for compensation, and straight length requirements. These are to be read in conjunction with Fig. V/3.5.0-2.

1. **Basic meter installation requirements:** The following are the basic installation requirements to be followed and/or met, in addition to those discussed in Section 3.5.1.
   - Check for a selected meter suitable for the process conditions. This is especially important for cryogenic and high-temperature applications.
   - For high-temperature and cryogenic applications proper insulation should be used. Also, the use of extended bonnets would be a good choice.



RESTRICTION AT		VORTEX		SWIRL	
UPSTREAM (UR)	DOWNSTEAM (DR)	UD	DD	UD	DD
NONE– MINIMUM STANDARD REQUIREMENT	STANDARD MINIMUM	15D	5D	3D	1D
SINGLE RIGHT ANGLE BEND SAME PLANE	SAME AS UPSTREAM	20D	5D	3D	1D
DOUBLE RIGHT ANGLE BENDS SAME PLANE	STANDARD MINIMUM	25D	5D		
SINGLE RIGHT ANGLE BEND DIFFERENT PLANE	STANDARD MINIMUM	40D	5D		
PIPE RDUCER	PIPE REDUCER	15D	5D	3D	1D
PIPE EXPANDER	PIPE EXPANDER	18D	5D	3D	3D
ANY TYPE VALVE	ANY TYPE VALVE	50D	5D	5D	1D
NONE MINIMUM STANDARD REQUIREMENT	CONTROL VALVE	15D	5D	5D	5D

* CONTROL VALVE AT OUTLET ONLY

FIGURE V/3.5.0-2 Vortex/swirl meter installation requirements. (A) Meter PT tapping for compensation. (B) Meter straight length requirements. *Developed based on data from ABB. Courtesy: ABB.*

- For high−medium-temperature applications (>150−200°C) the sensor should be installed in such a manner that the electronics are toward the side/downward to avoid high-temperature effects.
- Instrument to be located at the lowest point to insure meter flooding and that the meter is never dry.
- Compliance with the ambient conditions.
- Ambient temperature and media temperature are interrelated and so should be taken care of as per manufacturer's recommendations.
- Use of block and bypass valve normal with inline meters.
- Compliance with the required minimum interval for removing the transmitter and replacing the sensor [21].
- To avoid pressure vibration, at zero with suitable fitting gates [21].
- Matching of the flow meter sensor and the pipe internal diameter.
- Damping device to be used for pumps and compressor to avoid pulsating flow.

- All necessary precautions should be taken care of, for avoidance of any chance of cavitations, especially for pressure loss and damping.
- Compliance with inlet and outlet straight section detailed in Subsection 3.5.2.3 below.

2. **Tapping points and control element:** Some flow meters have integral temperature- and optional pressure-sensing devices. When separate pressure and temperature tappings are done, connections (pressure, temperature) should be located downstream of the flow meter, as shown in Fig. V/3.5.0-2A. As shown therein, the pressure tapping shall be before the temperature tapping. Control elements like the control valve/gate, etc. should be located at the downstream side only.
3. **Straight length requirements for various restrictions:** As indicated earlier for meter installation, there is a requirement of good flow profile. To meet with this requirement there are straight pipe length requirements for various restrictions. Such requirements have been illustrated in Fig. V/3.5.0-2B. From there it is clear that requirements are less for a swirl meter as it has built-in flow conditioning. For some cases, as seen in Fig. V/3.5.0-2B, there is a long straight length requirement for some severe upstream disturbances (especially for the vortex meter). The long, straight lengths of pipe requirements can be reduced by the use of flow-straighteners and flow-conditioning tubes detailed separately in Chapter XI. Short general guidelines are indicated in the table given in Fig. V/3.5.0-2B. This has been developed mainly based on data from ABB (Courtesy: ABB).

3.6.0 Insertion Type Vortex Meter

As indicated earlier, vortex meters are available in insertion types also. The advantage of this type of measurement is that these can be used for retrofit application, because insertion style vortex meters can be installed without disrupting flow. Also, as these are insertion type, the meter cost is independent of pipe size. However these types of meters have moderate accuracy.

3.6.1 FEATURES OF INSERTION TYPE VORTEX METER

The following are a few major features available with insertion type vortex type flow meters.

On account of built-in compensating pressure and temperature sensor, it is possible to measure and compute mass flow.
It is possible to compute the energy flow of steam [27].
No moving parts—less maintenance.
Easy to install without disrupting the process.
Smart communication using HART protocol and fieldbus.

3.6.2 APPLICATION

These can be utilized for any process plant, however they are used for energy audit and performance measurements for steam applications, compressed air systems, and industrial gas applications.

3.6.3 SPECIFICATION

The following is a short specification for insertion type vortex meter:

1. **Process pressure:** 103 bar;
2. **Process temperature:** −200 to 260°C;
3. **Ambient condition:** Temperature: −40 to 80°C;
4. **Sensor:**
   - *Flow:* Piezoresistive sensor;
   - *Temperature:* Pt 100 @ 0°C RTD;
   - Pressure sensor;
5. **Material:** Stainless steel 316L (wetted parts);
6. **Accuracy:**
   - *Liquid 0.7% AR volumetric mass:* >1.0% AR;
   - *Steam/gas 1.0% AR volumetric mass:* 1.5% AR;
7. **Repeatability:** 0.2% AR;
8. **Stability:** 0.2% AR for 1 year [27];

9. **Pressure loss:** Variable with range;
10. **Process connection:** Flanged 2−3″ ANSI 150/300 lb on pipe connection;
11. **Versions:** Integral and remote.

3.7.0 Discussions

For modern vortex/swirl meters, operating with a HART/fieldbus system the following checks can be performed electrically.

- Wet verification and calibration, as required to be carried out as per manufacturer's recommendations;
- Electronic verification of meter by flow simulation;
- Sensor response verification and analysis;
- Meter body/shedder bar verification;
- Wet calibration as per manufacturer's recommendations.

From the entire discussions on vortex/swirl meters it can be seen that this modern flow-metering technology is very useful for measurement of liquid, steam, and gas services with good accuracy. However it is not suitable for abrasive liquid, or liquid with dirt. Also, some limitations come from the Reynolds number.

3.8.0 Vortex Mass Flow Measurement (Multivariable Version)

The vortex mass flow meter has an integrated flow convertor, a mass calculator along with a PT100/1000 temperature sensor, integrated pressure sensors, and a flow sensor in one unit. The temperature and pressure sensors are installed inside the shedder bar with full protection. There is no need to install external temperature and pressure sensors or an external square root extractor. Also, they are equipped with suitable digital signal processing units for flow computation as well as vibration compensating. These are available with a 4−20 mADC/RS link with MODBUS, HART. Normally these instruments work with a loop power of 24 VDC.

We now look at another popular flow measurement technique based on fluidics.

4.0.0 FLUIDIC TYPE FLOW METERS

When one recalls Subsection 1.2.2.9 of Chapter I, it will be found that fluidics basically is a branch of fluid dynamics using small interacting flows and fluid jets to perform some typical functions. In the 1960s, Tippetts studied feedback systems of fluidic oscillators. From the observations it was found that the frequency of oscillation is proportional to flow over a wide range of fluid flows. Later this principle was utilized in developing actuators and flow meters. Another issue related to these types of flow meters is that they do not have any moving parts. *Now what is a fluidic oscillator?* Fluidic oscillators are devices with no moving part, that can generate oscillating jets of fluids at high frequencies. This phenomenon is widely used in windshield washer fluid dispensers in automobiles. There have been a number of meters developed on this basis. Though theoretically these flow meters can be used in any fluid yet, they are mostly used in liquid applications. Although the process has been known for quite some time, these meters did not gain much demand on account of their poor accuracy and the range of measurement available.

4.1.0 Basic Theory of Measurement

From Bernoulli's pressure equation it has been established that pressure head and velocity head can be transformed from one head to another whilst keeping the total energy the same. Thus, in a jet, high-pressure fluid with lower velocity is transformed into low-pressure fluid with high velocity. The Coanda effect can be utilized to control the jet with the help geometry of the oscillation chamber. Therefore fluidic oscillation can be created by the Coanda effect (1926). Also, as stated earlier, the fluidic oscillation of high frequency is proportional to the velocity of the fluid. Therefore, by sensing the high-frequency oscillation, velocity, flow can be measured. This is the background of flow measurement using the Coanda effect. The fluidic oscillator under question, works on formation of different pressures on either side of the jet to regulate the

direction of the flow. With the help of Fig. I/3.1.3-3, this has been explained in Subsection 1.2.2.9 and 3.1.3.3 in Chapter I. Let us now look at this in more detail. In this connection Fig. V/4.1.0-1 and I/3.1.3-3B may be referenced. As is seen in Fig. I/3.1.3-3 it is clear that there two major parts viz. flow tranquilizer and oscillator.

1. **Flow tranquillizer:** A flow tranquillizer is a kind of flow conditioner that eliminates the effect of flow profile and piping configuration on meter performance. A typical flow tranquillizer is depicted in Fig. V/4.1.0-1 (LHS). As shown in this figure there are three parts including a perpendicular wall, and division of flow into two paths for flow stabilizing.
2. **Jet formation and energy balance:** As stated earlier, jet formation is achieved by reducing the flow path to the fluid (in the fluidic meter), and then allowing it to expand suddenly in the form of an oscillation chamber. From Bernoulli's theorem applying conservation of energy one gets

$$P_1 + 1/2\rho v_1^2 = P_2 + 1/2\rho v_2^2 + E_n. \quad (V/4.1.0\text{-}1)$$

where P_1 (upstream pressure) > P_2 (downstream pressure), and naturally v_2 (downstream velocity) > v_1 (upstream velocity) and E_n accounts for the frictional loss, sensing energy—from conservation of energy. Thus the differential pressure at the exit is the key for the jet and there is additional effect of the jet separating from the boundaries. This was seen during our discussions in Chapter I.
3. **Coanda effect and oscillating chamber:** When the jet is connected to a relatively stationary fluid, a part of the stationary fluid

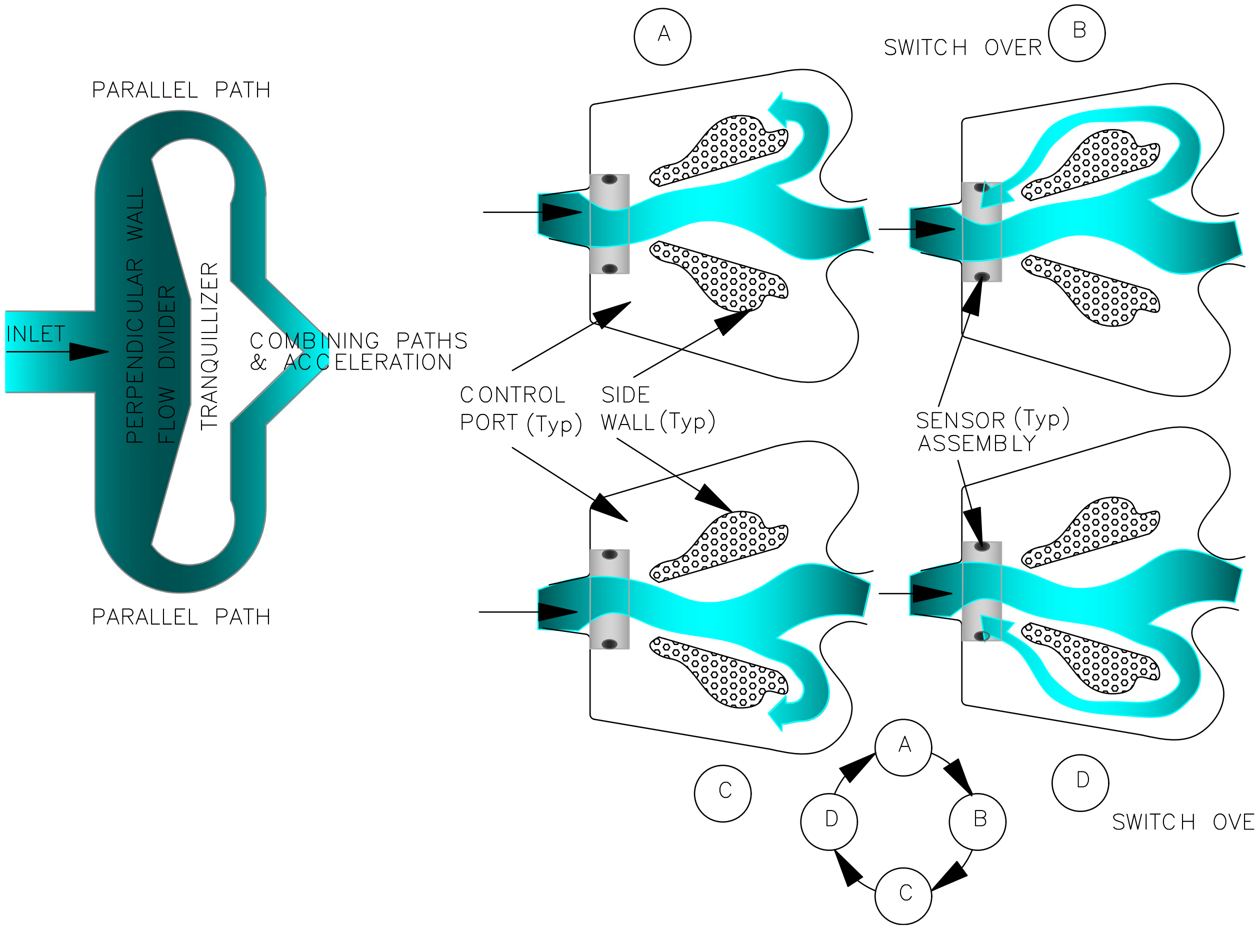


FIGURE V/4.1.0-1 Fluidic oscillation. *(Tranquilizer shown separately in LHS, refer Fig. I/3.1.3-3A for complete connection. Here oscillation concept has been explained in details).*

goes along with it. When there is a wall/obstruction near the nozzle angled away from the nozzle then, at an angle with the direction of the jet, the stationary fluid which would go along with the jet will be removed from the space between the jet and the wall/obstruction. This will finally result in bending of the jet toward the wall.

From these discussions it is clear that the internal geometry of the oscillating chamber is the cause of the jet being deflected from the central position and trying to be attached to one of the side walls. This is possible due to DP across the jet. If a sufficient volume of fluid is then introduced into the control port on *that* side, as feedback, then the jet will switch to the opposite side wall due to the feedback. *Why?* As the flow increases, it is pushed as feedback in the control port. Feedback will intersect the main flow and would increase the difference in pressure between either sides of the jet (taking more fluid from the other side, also more fluid through feedback in the node to increase pressure at the node). Once it crosses, the stiffness of the jet will cause a switch over of the jet to the opposite direction. This is known as a *Coanda effect.* There is an oscillating chamber in this type of meter. This chamber acts as an obstruction to the jet, which releases the fluid here. This chamber along with two side walls regulates the changes in pressure on either side of the jet. The entrapped/constraint volume of fluid on either side of the jet during switching over is known from P_1 and P_2. The amount of fluid necessary for switch over is therefore a function of the entrapped/constraint volume of fluid on either side. With the help of feedback the entire operation is repeated as explained in Fig. V/4.1.0-1 (RHS). Therefore, a continuous, self-induced oscillation of the flow between the side walls of the meter body is repeated. The frequency of oscillation is a linear function of the volumetric flow rate when the associated Reynolds number is above the minimum threshold. So, if F is the frequency of oscillation, and q is the flow of fluid then **F = Kq**. Here is K meter factor. Later we will look out for the Reynolds number and K factor for the meter. There is a theoretical minimum flow rate above which the phenomenon can take place.

4. **Momentum exchange method:** The fluid oscillations in momentum exchange type meters occur due to the fluidic phenomenon of momentum exchange. The geometrical shape of the meter body is such that the main flow of fluid passes through the nozzle. On account of the jet with two free passages in front, the jet will be directed toward one or other side of the meter body as shown in Fig. I/3.1.3-3B. Because of the kinetic energy of the jet of fluid, fluid will be forced to cross the entire free passage and create a flow pulse feedback. This flow pulse will travel through the feedback passage and exert a force on the main jet. The momentum of the feedback fluid will have momentum exchange with the main flow. *This momentum exchange phenomenon is somewhat analogous to a car moving in the slower lane moving into a lane where the cars are moving faster. When the slower car comes to that lane, faster cars coming from behind have to slow down to allow the slow car to accelerate.* Therefore, the feedback fluid will cause deflection of the main flow in the other/opposite feedback passage. With repetition of this feedback action (in both feedback passages alternately), the result is sustained oscillation. The sensor located in the feedback passage detects the fluid pulses which will be conditioned by a signal conditioner to produce the required output.
5. **Reynolds number and K factor:** The Reynolds number (Re) characterizes the flow. We know that Re is a function of dynamic viscosity (μ), density (ρ), fluid velocity (v), and restriction (here nozzle) width (d) and is given by

$$\mathrm{Re} = \frac{\rho \cdot d \cdot v}{\mu} \qquad \text{(V/4.1.0-2)}$$

As stated above there will be minimum flow rate necessary for the meter to function. The fluidic meter is characterized once, after that there will be an incremental volume of fluid at metering temperature and pressure, needed to switch over. This is determined at the time of calibration for the meter. This volume is reciprocal of the *meter factor* K. The meter is then characterized in terms of meter factor K. Now, like any other meter K factor, which quantifies the pulse/volume, it is found for a range of Reynolds number, a given pressure, temperature flow rate, and fluid composition by suitable interpolation technique. It has been found that the K factor of oscillatory meters varies with Reynolds number. Therefore, it is better to plot the K factor versus the Reynolds number. Such curves are available from the manufacturers. Actual meter K factor performance is a function of meter *design and fluid type* flowing through it. Normally there is a region on the curve where the K factor is essentially *constant*. This is the normal operating region for oscillating flow meters and, in this region, the accuracy is also good.

6. **Sensing method and electronic processing:** It has been established that the frequency of oscillation bears a linear relation with volumetric flow. So, for sensing it is necessary to determine the frequency of oscillation. A pressure detector or thermal detector could be used to determine the frequency of oscillation. As shown in Fig. V/4.1.0-1B (RHS), there are two sensors set uniformly across the jet. As the jet flips between the two sides there will be a momentary difference in signal between the two sensors. This will be signaled electronically to the signal processor where the frequency of oscillation will be determined. The meter electronics can produce a pulse, standard analog (4−20 mADC through converter), or digital output. Apart from this the meter would have self-diagnostic and communication facilities.

4.2.0 Meter Categories, Feature, Applications and Performance

4.2.1 METER CATEGORIES, FEATURES AND APPLICATIONS

In this section meter categorization, features of the meter, and application areas will be briefly discussed.

1. **Meter categories:** From the above discussions it is clear that fluidic flow meters can also be classified as oscillatory flow meters. However, as the type of flow meter in question utilize the fluidic characteristics for their functioning, i.e., they utilize specially designed geometric shapes to create an environment to produce self-induced, sustained oscillations by interacting between flow streams. In Section 1.1.0 of this chapter, the flow meter types have been classified as fluidic meters. From the discussion presented above it can be seen that the frequency of oscillation is accurately proportional to the volumetric flow rate. So, the frequency of oscillation is measured to determine the flow and one can consider this as an inherently digital device. There are several categories of oscillatory flow meters, each with unique geometry and application characteristics. However, in this book two main types of flow meter will be covered and these are Coanda effect fluidic flow meters and momentum exchange fluidic flow meters. Truly speaking there is not much difference between the two meter types; for the momentum exchange type of meter there is no specific need for the side walls and they can be utilized for higher viscosity.
2. **Fluidic meter features:** Fluidic meters show the following features for which they have gained some popularity, even in custody transfer applications.
   - Frequency of oscillation is directly proportional to volume flow, i.e., linear relationship.
   - The meters can offer turndown of 30:1.

- The measurement is unaffected by shock, vibration, or ambient temperature.
- For a given Reynolds number range, measurement is unaffected by density.
- There is no requirement for an impulse line and there are no moving parts in the meters.
- Flow over a range of around 400% possible.

3. **Application area:** Theoretically meters can be utilized for measurement applications of both gases and liquids but in actual operations, it is more popular in liquid measurements:
   - Fuel oil flow measurement in burners;
   - Cryogenic flow measurement;
   - Measurement of nitrogen and ammonia in fertilizer plants;
   - Wastewater flow measurement;
   - Liquid ammonia applications (low lubricity);
   - Batch control operation.

4.2.2 PERFORMANCE CHARACTERISTICS OF FLUIDIC METERS

There are a few characteristic features of fluidic meters which should be taken into consideration for meter selection and use. These include the following:

1. **Meter error:** Meter error could be a function of flow rate or the installation condition or process condition of the fluid. Normally both upper and lower limits are specified. Also, based on calibration, there could be a performance curve given by the manufacturers to restrict the meter operational range.
2. **Pressure loss:** From the discussions in basic theory one discovers that there is a need for obstruction in flow meters based on the Coanda effect. Therefore it creates a restriction in the pipe and there will be pressure loss on account of the meter. Therefore it is essential to size the meter, taking into consideration the pressure loss specified by the manufacturer. Otherwise there could be damage to the flow meter due to high flow and pressure drop. Typical pressure loss could be as high as 40 kPa for flow of 35 L/s in 75 NB meter size.
3. **Back pressure:** As a consequence of pressure loss there could be the possibility of cavitations. It is therefore essential for minimum back pressure to be maintained. If minimum back pressure is P_b and pressure drop, vapor pressure, and atmospheric pressures are represented by ΔP, P_v, and P_{atm}. P_b (minimum) is given by:

$$P_b = 3 \times \Delta P + 1.25 \times P_v - P_{atm} \quad \text{(V/4.0.2-1)}$$

   (This equation may be compared with Eq. V/2.4.2-1 for a turbine meter.)
4. **Maximum and minimum flow rates:** Normally the maximum flow rate specifies the maximum flow that can be measured within the specified error limit. However this range can be exceeded with higher measurement error. Often the maximum flow rate is limited by the sensor range. The minimum flow rate is guided by the uncertainty limit chosen. As already discussed, Reynolds number and the ability of the sensor to detect jet creates the limit for the minimum flow rate.
5. **Viscosity effect:** Viscosity has a direct impact on the measurement of flow by the fluidic meter. Since viscosity affects the Reynolds number, which has a direct influence on flow meter performance, there are two minimum values of Reynolds number within which the meter can operate and beyond which the same meter is nonoperable Refer Fig. V/4.2.2-1. The two minimum Reynolds numbers mentioned indicate the limits for the linear operating region and also the nonlinear but operating region. This is clear from Fig. V/4.2.2-1 (developed based on Ref. [28]). In Fig. V/4.2.2-1 there are two sets of curves shown. One is for the Coanda effect meter and the other for the momentum exchange meter. In the case of the momentum exchange meter the nonoperating region, *as well as* the nonlinear operating region, has a much lower area, *meaning* that in the case of the momentum exchange meter it can withstand much lower Reynolds numbers, i.e. it can handle *more* viscous fluid than the Coanda effect meter. Another important point here to be noted is that the operating

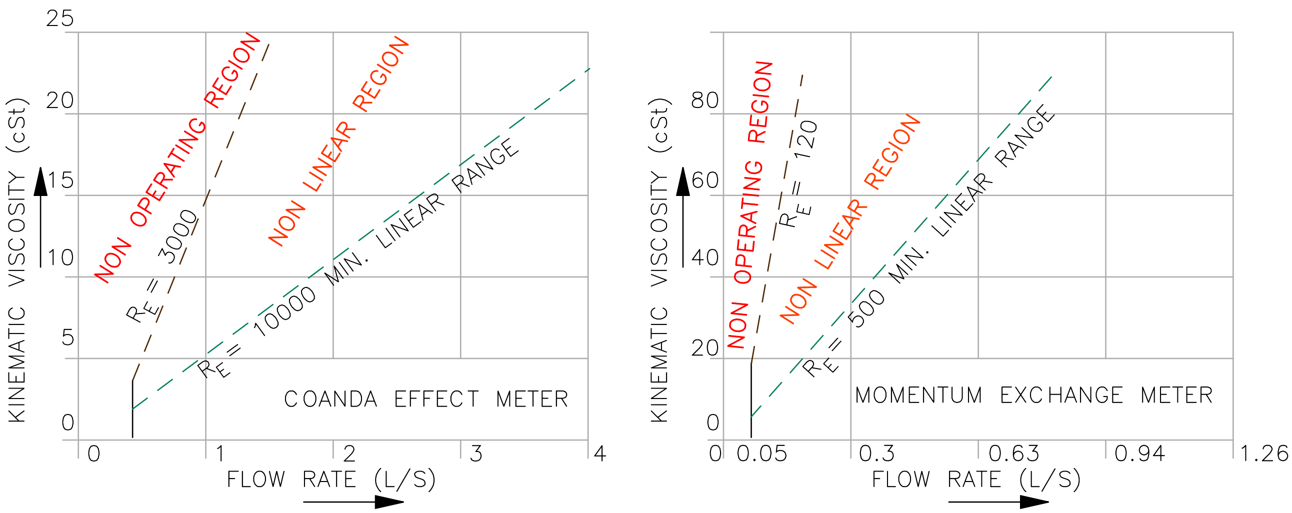


FIGURE V/4.2.2-1 Viscosity effect on fluidic meter. Set of curves shown here is for 25 mm meter size. There will be variation of curves for different sizes. Also note the changes in minimum Reynolds numbers for operating and linear operating ranges for COANDA effect meter and momentum exchange meter. *These figures have been developed based on Model 141 Flow Meters, Product Information, Fluidic Flow Meters, Catalog; PI14–2Rev:1, March 2002. http://www.fluidicflowmeters.com/pdfs/141-New.pdf. An Introduction to Non Invasive Ultrasonic Flow Metering, Good Practice Guide, National Measurement System, TUVNEL. http://www.tuvnel.com/_x90lbm/An_Introduction_to_Non-invasive_Ultrasonic_Flow_Metering.pdf. Courtesy: Fluidic Flow Meters.*

region and linear operating region for both types of meters will vary with meter size (i.e., for both types of meters the set of curves will be different when the meter size changes).

6. **Mounting:** Flow meters can be mounted horizontally or vertically, on an inclined plane with flow directed upward. The mounting position does not have any effect on the performance of the meter, as long as the meter is full with the fluid in question.

4.3.0 Coanda Effect Flow Meter

Having gathered some knowledge about the fluidic meters now brief discussions on commercially available Coanda effect flow meters are given.

4.3.1 RANGE LIMITS AND ACCURACY

Range limits: Normally Coanda flow meters are available in different sizes, of which 25–75 mm are mostly used. Minimum Reynolds number, flow rates, and accuracy are interrelated and are presented in Table V/4.3.0-1. The data presented are from a reputed manufacturer.

TABLE V/4.3.0-1 Minimum Reynolds Number and Flow Range for Fluidic Flow Meters

Size (mm)	Min. Re	Min. Flow (L/s)	Max. Flow (L/s)	Accuracy %AR
25	10,000	0.2	3.5	1.25
40	15,000	0.5	8.2	1.25
50	20,000	0.7	13.5	1.25
75	30,000	1.45	29	1.5

Re, Minimum Reynolds number; Minimum flow and maximum flow are two flow limits. Flow unit, L/s.

4.3.2 OPERATING CONDITIONS

The following are typical operating and ambient conditions:

1. **Operating pressure limit:** ANSI 150 lb class for flange;
2. **Operating temperature:** −40 to 170°C.

4.3.3 PERFORMANCE DATA

The overall performance of the meter could be as follows:

1. **Accuracy:** ±1.25% AR−1.5% AR;
2. **Repeatability:** 0.2% AR;
3. **Turndown:** 30:1 possible, normal 15:1;
4. **Ambient effect:** 1% accuracy for 150°C.

4.3.4 OTHER RELEVANT DATA

The following are a few important mechanical data:

1. **Process connection:** Normally meters are available in wafer/and sometimes flanged connections. Flanges could be international standard equivalent to ANSI 150 lb class of a size suitable for the meter size.
2. **Pressure loss:** Pressure loss is quite high as per manufacturer's curve of pressure loss against flow rate for different meter sizes. Typically for 25 mm meter size at highest flow rate of 3.7 L/s could be 40 kPa.
3. **Back pressure:** Refer to Subsection 4.2.1.3.
4. **Electrical connection:** ½″NPT/BSP M20 standard.
5. **Materials of construction:**
   - *Meter body/housing:* Stainless steel 316L;
   - *Sensor:* Stainless 316/Hastalloy;
   - *Flange:* CS/SS;
   - *Gasket:* Neoprene;
   - *Nonwetted part meter housing body:* Aluminum.
6. **Hazardous applications:** possible with certification from appropriate authority.
7. **K factor:** Refer to manufacturer data.

4.4.0 Momentum Exchange Meter

The momentum exchange meter is another kind of fluidic meter where fluidic oscillation is generated in a way different from that in a Coanda effect flow meter. This is already explained in Subsection 4.1.0.4. Now, brief discussions on momentum exchange flow meters will be presented. Basically there is not much difference between the two types of meter. One salient difference is that the momentum exchange meter does not require turbulent flow to be maintained for its operation. It can handle more viscous fluid than a Coanda effect flow meter. However, the flow-handling capability and accuracy of measurement of the momentum exchange meter are less when compared with the Coanda effect flow meter. Meter accuracy is around 2% AR for a momentum exchange meter.

4.4.1 RANGE LIMITS AND ACCURACY

Range limits: Normally momentum exchange flow meters are available in different sizes, of which 20−40 mm are mostly used. Minimum Reynolds number, flow rates, and accuracy are interrelated and are presented in Table V/4.4.0-1. The data presented are from a reputed manufacturer.

TABLE V/4.4.0-1 Minimum Reynolds Number and Flow Range for Fluidic Flow Meters

Size (mm)	Min. Re	Min. Flow (L/s)	Max. Flow (L/s)	Accuracy %AR
20	400	0.02	0.5	2
25	500	0.04	1.0	2
40	500	0.12	3.5	2

Re, Minimum Reynolds number; Minimum flow and maximum flow are two flow limits. Flow unit: L/s.

4.4.2 OPERATING CONDITIONS

Operating conditions are similar to a Coanda effect flow meter.

4.4.3 PERFORMANCE DATA

Overall performance of the meter could be as follows:

1. **Accuracy:** ± 2% AR;
2. **Repeatability:** 0.25% AR;
3. **Turndown:** 30:1 possible normal 12:1;
4. **Ambient effect:** 1% accuracy for 160°C.

4.4.4 OTHER RELEVANT DATA

The following are a few important mechanical data:

1. **Process connection:** Normally meters are available in wafer and sometimes flanged connections. Flanges could be international standard equivalent to ANSI 150 lb class of size suitable for the meter.
2. **Pressure loss:** Higher than with a Coanda effect meter. From the manufacturer's curve of pressure loss against flow rate for different meter sizes this can be found out. Typically for 25 mm meter size at highest flow rate at e.g., 3.5 L/s could be 6.8 bar.
3. Other specification details are similar to what has been enumerated in connection with the Coanda effect flow meter.

With this the discussion on fluidic flow meters and oscillatory flow meter comes to an end. Electrical velocity type flow meters are now discussed.

5.0.0 ELECTROMAGNETIC FLOW METERS (EMFMs)

Electromagnetic flow meters (EMFMs) working on velocity measurement principles are true nonintrusive (for capacitive sensing noninvasive also) flow-measurement devices. Details on nonintrusive and noninvasive measurements have been explained in Fig. V/5.7.0-2. The history of the development of this meter starts in 1915 when the Americans M.W. Smith and Joseph Slepian tried to measure the speed of a boat utilizing magnetohydrodynamics. Briton E.J. Williams in 1930 utilized a similar idea in a closed conduit. After World War II, with rapid developments in science and technology, there have been higher requirements for flow measurements and flow-metering technology which have developed rapidly as people could not rely on the existing systems of flow measurements. The commercial electromagnetic meter was first established in 1952 with a Tobi meter. The British scientist J.A. Shercliff published the "Theory of electromagnetic flow-measurement" in 1962, therefore electromagnetic flow meters based on Faraday's electromagnetic induction principle have been on the market for over 50 years. With reference to Fig. I/5.0.0-1, the overall market share of electromagnetic flow meters is around 17%, but in process plants it enjoys more than 20% of the flow market share. *What is the theory behind this measurement?*

5.0.1 BASIC THEORY OF MEASUREMENT

When one recaps Subsection 3.1.3.6 of Chapter I one would find that electromagnetic flow meters' working principle is based on Faraday's law of induction that states that when a conductor of length l (m) is moving with a velocity v (m/s) through a perpendicular magnetic field of flux density B (Tesla), a voltage E will be induced in it that is proportional to the velocity of the conductor. So, induced voltage will be given by $E = \overline{B} \times l\overline{v}$. As this is cross multiplication of vectors, induced voltage will be in the direction perpendicular to both the vectors. since the direction of velocity and magnetic field are perpendicular to each other, and so induced voltage E will be perpendicular to both the vectors and can be expressed as

$$E = B \cdot l \cdot v \qquad (V/5.0.1\text{-}1)$$

This characterization of the laws of induction is applied to the movement of a conductive liquid at a velocity v, in a pipe of internal diameter D

(the length of conductor/conductive fluid), kept across a perpendicular magnetic field of strength B. So, as per the above law of induction, there will be an induced voltage across E in the conductive fluid and it will be given by

$$E = B \cdot D \cdot v \text{ or } v = \frac{E}{B \cdot D} \quad \text{(V/5.0.1-2)}$$

Two sensing electrodes, set at right angles to both the magnetic field and direction of velocity (i.e., flow), are used to detect the voltage that is generated across the flowing liquid. In this case, since magnetic strength "B" and pipe ID "D" are fixed, E is proportional to the velocity of the conductive fluid.

Again it is known that volume flow is given by putting the value of v from Eq. (V/5.0.1-2) into

$$q = A \cdot v \text{ or } q = A \cdot \frac{E}{B \cdot D} \quad \text{(V/5.0.1-3)}$$

or

$$q = \pi \frac{D^2}{4} \cdot \frac{E}{B \cdot D} = \pi \frac{D}{4} \cdot \frac{E}{B} \quad \text{(V/5.0.1-4)}$$

Therefore, as B and D are constant, volumetric flow q is proportional to the induced voltage E.

When the pair of magnetic coils is energized, a magnetic field is generated in a plane that is mutually perpendicular to the direction of velocity (flow) of the conductive liquid, i.e., along the longitudinal axis of the flow meter body. Therefore, on account of cross product of vectors, the voltage induced within the liquid is mutually perpendicular to both the velocity of the liquid and the magnetic field as shown in Fig. V/5.0.0-1A. The liquid can be considered as an infinite number of conductors moving through the magnetic field, with each element contributing to the voltage generated [9]. Therefore, any change in conductive fluid velocity (fluid flow) will cause a change in the instantaneous value of the induced voltage generated E as long as B is constant.

The induced voltage of the flow meter is actually the average of the voltage contributions across the metering cross-section. Also, the signal voltage generated is equal to the average velocity, irrespective of the flow profile.

5.0.2 PARAMETERS AND CONSTRAINTS

In this section the above theory will be looked at in detail to see what the constraints are or how the meter response can be changed.

1. **Conductivity:** From the discussions above it is clear that functioning of the meter depends on the fluid passing through the conduit being conductive. For normal proper functioning of the meter, minimum conductivity of the flowing fluid should be in the range of 5–20 μs/cm. However, for low conductive fluid (e.g., ~0.05 μs/cm) flow measurement by an electromagnetic flow meter is possible, by modifying the voltage measurement technique discussed in Section 5.0.3 in this chapter.
2. **Conductor length:** From Eq. (V/5.0.1-3) it can be seen that for a given velocity (flow) the induced voltage is limited by the length of the conductor D, i.e., pipe ID and the flux density B. Of these two parameters, D is fixed for a given pipe and hence cannot be changed.
3. **Pipe material and flux density:** Two coils generate the magnetic field that extends through the pipe, and should not be shunted by permeable pipe materials. *Austenitic steel* does not hinder the magnetic field, making this is a natural choice as a commonly used meter pipe material in electromagnetic flow meters. Flux density B is a factor which can be changed to modify E. If μ = permeability and H = magnetizing field strength (ampere-turns/m) then

$$B = \mu \cdot H \quad \text{(V/5.0.2-1)}$$

Here μ is dependent on the pipe, i.e., the iron–liquid gap combination (physical constraint of pipe and construction). Also, B can be increased by increasing H, which is a function of the

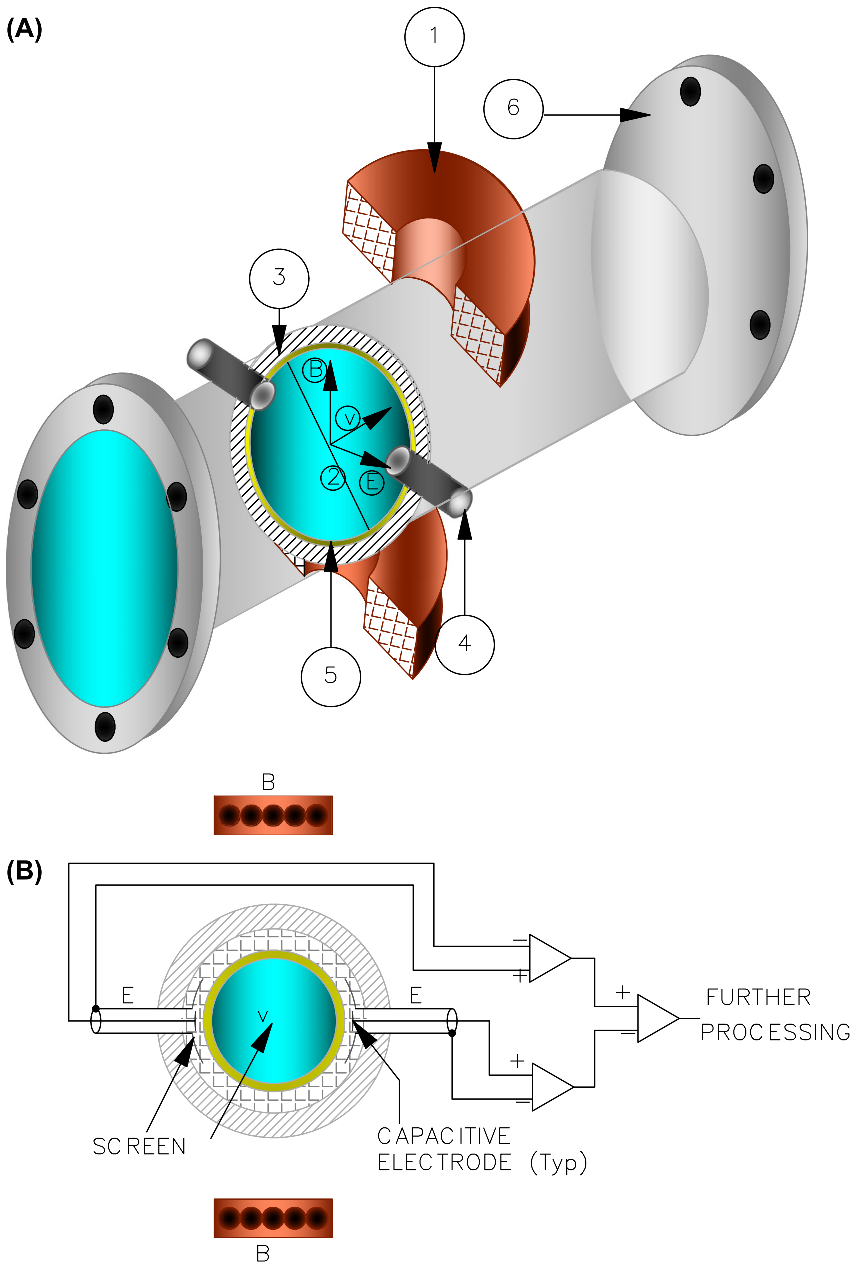


FIGURE V/5.0.0-1 Theory of an electromagnetic flow meter. (A) Galvanic sensing. *B*, magnetic field; *E* electrode potential; *v*, velocity due to flow. (1) Magnetic coil, (2) conductor length D (pipe ID), (3) conduit cross-section, (4) measuring electrode, (5) meter lining, (6) flanged end connection (typ), $E = B \cdot v \cdot D$; $A \cdot v = q$. So, q is proportional to E as others are constants. Electrodes galvanically connected to measuring fluid i.e., electrodes in contact with fluid. Not possible for very low conductivity fluid; (B) Capacitive sensing. In capacitive sensing two electrodes form capacitance with liner as dielectric for very low conductive fluid.

number of windings and its length in the coils and the coil magnetization current. Therefore, for the same velocity of a given fluid, induced voltage can be changed or increased by increasing the magnetizing current or coil design.

5.0.3 INDUCED VOLTAGE MEASUREMENT

The induced voltage is measured by electrodes by a galvanic method. Electrode impedance is a

function of fluid conductivity and meter size. In a conventional AC excitation system (discussed later) normal conductivity of fluid is around 5−20 μs/cm, and for DC excitation it is approximately up to 1 μs/cm in the lower side. For very low conductive fluid the galvanic method of measurement will not do, here one has to go for capacitive type sensing. In this section short discussions are put forward on these two methods.

1. **Galvanic measurement:** The induced voltage E is measured by means of two metallic electrodes that are in electrical contact with the measuring medium, like a liner (nonintrusive) as shown in Fig. V/5.0.0-1A. Electrodes are inserted penetrating the metal pipe to keep in contact with the flowing conductive fluid. In the galvanic method, the electrode pair is electrically isolated from the metallic pipe walls by nonconductive liners to prevent short circuiting of electrode signals. With the help of electrode holders with sealing, electrodes are held at positions where maximum potential differences occur [9]. In a galvanic system at the interface between the electron conductive metal electrodes and the ion conductive liquid there may be a polarization voltage which varies with ambient condition and between electrodes [1]. This is a kind of noise. To get rid of noise issues suitable shielding is used for electrode connection. Since in the galvanic method, electrodes are directly in contact with fluid, for some measuring media there is the chance of insulating coating deposits on the electrodes. These coatings interrupt the signal circuit and deteriorate the meter performance. Therefore, there may be need for continuous/periodic cleaning. Ultrasonic/electrical cleaning is often used to get rid of expected insulating coating. In electrical cleaning, the instrument first detects very low conductivity while measuring the induced potential. The instrument then applies around 60 VAC across the electrodes. After approximately 1 min the electrolytic action starts to form microporous paths through the isolating "barrier." As these paths become progressively larger, the isolating barrier starts to break away from the electrode [5]. A degree of self-cleaning is possible sometimes by using pointed electrodes which extend into the higher-velocity regions of the flow. This is not possible in all applications, such as greasy layer mechanical cleaning, where removal of the meter may be necessary. For deposit problems, as well as for very low conductivity fluid, other means such as capacitive types are used.
2. **Capacitive measurement:** In capacitive sensing the major difference is that plate electrodes are not in direct contact with flowing fluid. Two numbers of metallic area electrodes are located behind the meter liner (or are attached to the outside of the flow tube of ceramic, for example). These metallic area electrodes (burried/embedded in liner) are two capacitors with the process-wetted inner wall whose dielectric is the liner. These electrodes pick up the electromotive force induced by the flow of the fluid due to magnetic field, through the capacitances. Thus the induced voltage charges the capacitors and the same are measured by two sets of preamplifier stage as shown in Fig. V/5.0.0-1B. This preamplifier circuit is connected to an external signal processing circuit for measurement of proportional flow. *Since the capacitance must be at least 20 pF, minimum area dimension limits exist which cannot be met by electromagnetic flow meters with a nominal diameter below DN 25* [1]. For precise measurement, getting rid of capacitance loss or noise influence, the shielding between the meter tube and measuring electrode is essential. Also, proper earthing of the shield is very important. With this arrangement very low conductivity (e.g., up to 0.05 μs/cm) fluid can be measured.

5.0.4 MAGNETIC FIELD CHARACTERISTICS

Conceptually, the electromagnetic flow meter was designed with a homogeneous magnetic field. However, for a given velocity it was

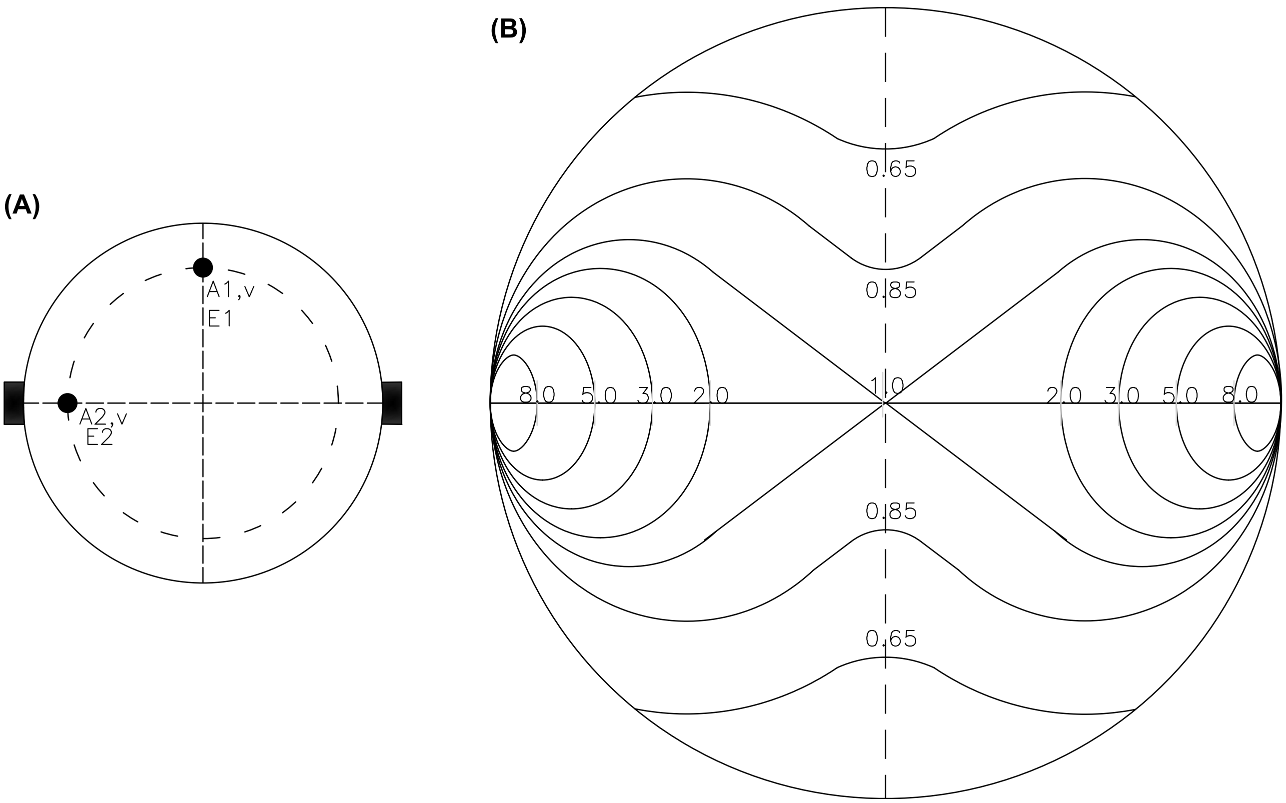


FIGURE V/5.0.0-2 Magnetic field characteristics. (A) Variation of induced voltage. (B) Weighing factor distribution.

observed that the medium does not generate the same voltage signal in the electrodes at all points, as shown in Fig. V/5.0.0-2A. Subsequent to his research, Ketelsen designed a magnetic flow meter making use of a "characterized field." The induced voltage E measured at the electrodes is the sum total of all the elemental voltages induced in the total area of the magnetic field covered in the meter tube, i.e., the ratio of the partial voltage due to each element to the total measuring voltage E at the electrodes. As mentioned earlier, this is a function of the geometric location (say A1/A2) of that element. Ketelsen brought the concept of the distribution of the weighing factor (W) of the elemental voltages as shown in Fig. V/5.0.0-2B.

At the center, W has an assumed value of "1." It is obvious that the elemental voltages induced in the vicinity of the electrodes have a greater effect than those induced in the polar region. The weighting factor W concept is used to define the location-related magnitude. With a magnetic field design in which the field strength is inversely proportional to the weighting factor a method of compensation was discovered [1]. As per this concept, the magnetic field strength increases with the low weighting factor areas, conversely areas with higher W will have a lower magnetic field strength as indicated in Fig. V/5.0.0-2B. So, the product of the weighing factor W and the field strength B is constant over the entire cross-section, i.e., $\boldsymbol{W \cdot B} = \boldsymbol{Constant}$. Therefore, all the elemental voltages are the same and a nonsymmetrical flow profile causes no error. For actual implementation of this concept it is recommended that short inlet sections, 3−5 times the pipe diameter in length, be installed upstream of the electromagnetic flow meter to effectively eliminate the effects of upstream flow disturbances [1].

5.0.5 MAGNETIC FIELD EXCITATION SYSTEM

In the previous section it was noted how the magnetic field is distributed geometrically. Then *how is this magnetic field generated?* For proper functioning of an electromagnetic flow meter a strong magnetic field is essential. A permanent magnet could be the best solution, so that noise induced through the AC source (e.g., higher frequencies AC creates transformer action in the signal leads and in the fluid path) could be eliminated. Unfortunately, it will give rise to polarization voltages. Polarization is the formation of a layer of gas around the measured electrodes. When the amplitude of this polarization voltage, which is unpredictable, is large there would be a large error in measurement. Therefore, the system should be designed in such a way that both the major issues associated with AC and DC excitation can be eliminated. However, prior to that, it is necessary to know the types of excitation systems.

1. **DC pulsed excitation:** In a DC pulsed magnetic excitation system, the excitation takes place at a low frequency of 3−8 Hz. In this approach the flow measurement samples are taken when the coils are excited with, e.g., positive voltage, and the measurement value is stored. Then a second measurement of the induced voltage is taken when the coils are not excited. When the current to the magnet is turned on, a DC voltage is induced at the electrodes. So, during this time it is the sum of signal plus noise. When excitation is turned off, the signal represents only the noise. Subtracting the second measurement from the first measurement, noise is eliminated. In reality DC excitation is done with charging for a period of time in one polarity, waiting for some time then again reversing the polarity and exciting. Like the previous case in first measurement, the signal will be E+ noise and second case it will be (−)E + noise. By subtracting the second from the first would give the 2E signal. The result is a measuring voltage E proportional to the volume flow rate which is free from noise. This is referred to as automatic zero adjustment as it is stable zero even at measuring medium conductivities at the lower limit of 5 μs/cm [1].
2. **AC excitation:** In an AC excitation system, the AC signal from mains at 50 or 60 Hz creates the magnetic field. This is a comparatively older system but is still in use in some special applications, such as in filling systems where very short measurement intervals are coupled with exact valve closure characteristics or hydraulic transport of solids like in pulp and paper plants. There are two types of AC excitation systems, i.e., on−off excitation and plus−minus excitation. In this system the measurement is taken when there is no excitation and a second measurement when the coils are energized and the magnetic field has stabilized. AC excited systems are available from <50 Hz to as high as 5 KHz, of which a frequency of 400 Hz is most common. These give good noise rejection.
3. **Dual-frequency signal:** The DC pulse excitation system discussed above has a slower response time. To eliminate the same many use dual-frequency excitation. The idea behind dual-frequency excitation is to apply both methods and thereby benefit from the advantages of both: the zero stability of low-frequency excitation and the good noise rejection and high speed of response of high-frequency excitation [9]. Here a high-frequency signal is superimposed on a low-frequency signal. The low-frequency signal gives zero stability and immunity towards noise due to low conductivity, viscosity, slurries, etc. the high-frequency signal provides immunity. Output is sampled at high frequency. Therefore, it eliminates slurry noise and assures zero stability. Further details are available in Section 3.1.4 of Chapter VII also. Detailed discussions on excitation system has been presented in Section 5.3.2 also.

5.0.6 NOISE ISSUES

It is important to note that the amplitude of the induced voltage may be small in amplitude when

compared with external voltages and noise. The noise sources include the following:

1. **Stray voltage and noise**: Conductive liquid-filled meters, especially large meters, provide a good conducting path for ground current from an asymmetrical electrical system. The potential differential exists between the electrodes due to this ground current inducing external stray noise voltage. This is prevented by shunting the ground current around the meter through low-resistance grounded large copper wire.
2. **Transformer effect:** The signal line from an electrode with a measuring medium form a single loop in which there could be inductive coupling of the excitation circuit to cause what is known as transformer coupling/effect. Precise mechanical assembly and orderly placement of the lines minimize this voltage [1].
3. **Polarization noise:** In the case of galvanic measurement (Subsection 5.0.3.1), there is an electrochemical direct voltage which is at the interface between the *electron* conductive electrodes and the ion conductive liquid. The polarization voltage as already stated is a function of pressure/temperature and/or measuring medium composition. These values are unpredictable as they cannot be reproduced as they will be different at different electrodes. This is not applicable for capacitive measurement.
4. **Capacitive coupling noise:** There will be capacitive coupling between magnetic coils with signal line/electrodes. This coupling is a function of excitation voltage and medium conductivity. The use of screen in the cable could be a solution.
5. **Capacitive coupling with power circuit:** Similar to above there could be capacitive coupling of signal lines with power circuit.

5.1.0 Descriptive Details of Electromagnetic Flow Meters

The basic theory behind measurement has been already been discussed in Section 5.0.1 and for principles of measurement Subsection 3.1.3.6 of Chapter I. In this section short discussions on principles and description will be given.

5.1.1 DISCUSSIONS ON PRINCIPLES OF OPERATION

The principle of operation of an electromagnetic flow meter is based on the movement of the conductor—the flowing liquid through the magnetic field.

From Eq. (V/5.0.1-3), one gets the flow equation as $q = A \cdot \frac{E}{B \cdot D}$.

There are a few things that are very important, including that the pipe carrying the medium should not have any influence or hindrance on the field, i.e., there should not be any short circuiting of the magnetic field. For this it is necessary that the metering tube be manufactured from *austenitic steel*/nonferromagnetic material, such as stainless steel or nickel-chromium. Also, it is necessary to ensure no short circuiting of the two sensing electrodes through the tube wall. For this reason, for galvanic measurement these are insulated through a liner and in the case of capacitive sensing they are located outside/in the liner through the *shielding*. In addition to these there are certain design aspects of selection of filed excitation system, noise elimination, etc. We will now look into the description and constructional details.

5.1.2 DESCRIPTION OF A FLOW METER

1. **Basic description:** The basic element of a flow meter is a section of nonconducting pipe such *austenitic steel*/nonferromagnetic, ceramic, or glass-reinforced polyester pipe section lined with suitable material, i.e., Teflon, rubber, neoprene, or Kynar to name but a few. On alternate sides of the pipe section are magnet coils that produce the magnetic field perpendicular to the flow of liquid through the pipe. A pair of electrodes are mounted in the pipe in contact with the liquid, but insulated from the pipe. These electrodes should be selected in such a manner that there will be less chance of an insulating coating developing on them. In many applications, as indicated earlier, there is a need

for regular cleaning of electrodes by electrical or ultrasonic wave means. Also as indicated earlier, in capacitive sensing the major difference is that plate electrodes are not in direct contact with flowing fluid. Two sets of metallic area electrodes are located behind the meter liner (or attached to the outside of the flow meter pipe). The electrode pair axis is at right angles both to the magnetic field and the axis of the pipe. Positioning of the electrodes is vital. With reference to Section 5.0.4 above, the electrodes should be placed where there is maximum induction. When liquid passes through the pipe section, it crosses the magnetic field set up by the magnet coils. As per the principles of operation, there will be an induced voltage in the liquid and the amplitude of the induced voltage is directly proportional to the liquid velocity. The pair of electrodes conducts the induced voltage to the preamplifier stage where induced voltage is converted to the desired signal. For sensing, the electromagnetic flow meter consists of a sensor and a transmitter. The exterior part of the sensor consists of a housing, meter tube, and pipe connections. The sensor alone does not function, it requires a transmitter for remote transmission of the signal. There are two variants of transmitters, e.g., an integral transmitter and a remote mounted transmitter. The transmitter variants are defined by the appropriate housing arrangements [1]. In the case of remote transmission also there are some variations, such as some of the meters have 4−20 mADC output only. These are known as conventional electromagnetic flow meters. There are smart versions also, e.g., 4−20 mADC with superimposed HART protocol. Smart transmitters often have a fieldbus communication facility to support various fieldbus systems, such as PROFIBUS, Foundation fieldbus, etc. Most of the electromagnetic flow meters have a flanged process connection. Designs are available with sanitary-type fittings. In large pipe sizes, Dresser-type and Victaulic-type end connections are also widely used [9].

2. **Magnetic flow meter types:** Apart from normal inline electromagnetic flow meters, there are various other versions of the meters available such as:
   - Replaceable flow tube with external field;
   - Insertion type/Pitot tube type;
   - Electrodeless miniaturized type.

   There are other classifications of magnetic flow meters on the basis of field excitation, e.g.,
   - AC excitation system;
   - DC pulse excitation system;
   - dual-frequency excitation.

   Based on output type the meter can be classified as:
   - Conventional type with 4−20 mADC/pulse output;
   - *Smart version:* above output with HART Protocol;
   - *Fieldbus compatible meter:* to support fieldbus communication.
3. **Basic parts of an electromagnetic flow meter:** Electromagnetic flow meter assembly basically consists of the following parts:
   - Meter body;
   - Lining;
   - Magnetic field;
   - Electrodes;
   - Sensing detector;
   - Transmitter.

We now look into other detailed functioning of electromagnetic flow meters.

5.1.3 OPERATING, ENVIRONMENTAL PARAMETERS, AND PROTECTION FOR FLOW METERS

Listed below are salient process conditions normally supported by electromagnetic flow meters. It should be noted that values given are in the highest/lowest limit side and may not match with any particular type.

1. **Pressure (and derating):** Normally, up to a certain size of meter the pressure rating is guided by the flange rating, such as up to e.g., 600 mm size, it is around PN 10/16. However at lower sizes PN 40/ANSI 300 is also possible. Above that meters are available up to 16 bar. It is important to note here that the meter pressure rating is guided by the

flange material and pressure rating at different temperatures. This will be clear from an example: Suppose the meter has a carbon steel flange of rating say ANSI150, then the meter pressure rating as well as flange pressure rating will be 17.93 bar (260 psi) at 93.3°C (200°F), or 11.72 bar (170 psi) at 260°C (500°F). Similarly with a stainless steel flange in DIN PN16 the rating will be 15.1 bar (219 psi) at 80°C (175°F) or 14.1 bar (219 psi) at 180°C (356°F). These are standard ratings available from *flange data.* It should be noted that with an increase in temperature there will be pressure derating and with material of flange (even if the meter can withstand a higher rating with better material!) pressure rating changes.

2. **Temperature:** Temperature withstand capability up to 90−100°C is normal with integral transmitters. In the case of a remote transmitter, temperature up to 160°C is possible. Temperature range is also detected by the liner used, e.g., hard rubber temperature range −20°C (13°F) to 80°C (175°F) or Teflon upper range 80°C (266°F).
3. **Viscosity and density:** Performance is not affected by variations in density or viscosity.
4. **Conductivity:** Normal meter conductivity range is 5−20 μs/cm but it is possible to measure fluid with viscosity as low as 0.05 μs/cm.
5. **Environmental condition:** Typical ambient conditions for meters are as follows:
   - *Storage temperature:* −20 to 80°C;
   - *Ambient temperature during operation:* −20 to 60°C;
   - *Relative humidity:* Normal 85%; climate-proof design: 90%.
6. **Protection:** Normally meters have the necessary protection and protection certificates such as:
   - *Enclosure:* NEMA 4X/IP 66/67, IP68 designs are also available, e.g., from ABB;
   - *Explosion-proof:* Explosion/flame proof enclosure say, Ex-d, with certification from competent authorities;
   - *Intrinsic safety:* Intrinsic safe systems such as Ex ia with certification from competent authorities.

For details regarding enclosures, electrical classifications etc. author's book Ref. [22] may be referenced. It can withstand ambient temperature in the range −20 to 60°C and between −20 to 75°C in storage. Normally meters can withstand harsh ambient prevalent in industrial plant. However, for extreme conditions remote transmitter versions may be opted for.

5.1.4 METER K FACTOR AND PERFORMANCE DATA

1. **K factor/calibration factor:** From Eq. (V/5.0.1-3) one gets $q = A\cdot\frac{E}{B\cdot D}$. In order to have direct variation of q with E, other parameters such as A, B, D. Since A and D are mechanical values and they are constant for a given condition. The question now lies with making B constant. However, if a constant current source is used for excitation, B will be constant. This is a costly proposition. A compensation circuit shown in Fig. V/5.1.4-1A may be followed.

   Across a resistor R in the excitation circuit, a voltage drop E_{Ref} occurs which is proportional to the excitation current I and therefore the magnetic inductance B. The voltage E is also proportional to the induction B. When the ratio of these two variables E/E_{Ref} is calculated, the influence of the magnetic induction B is canceled.

   $$q = A\cdot\frac{E}{B\cdot D} \text{ or } q = A\cdot\frac{E}{D\cdot E_{Ref}} \text{ or } q = K\frac{E}{E_{Ref}} \qquad \text{(V/5.1.4-1)}$$

   K is the meter factor for calibration. For devices with pulsed DC excitation, the calibration factor K is replaced by the calibration factors for zero and the factor for span for each excitation frequency [1]. To get the standardized meter performance, the factory calibration procedure measures flow Q and output E, and *adjusts* K electrically. The manufacturer's catalog normally specifies the K factor. Often this factor is mentioned as the calibration factor.
2. **Meter performance data:** Like all other meters, the manufacturer's catalog specifies the

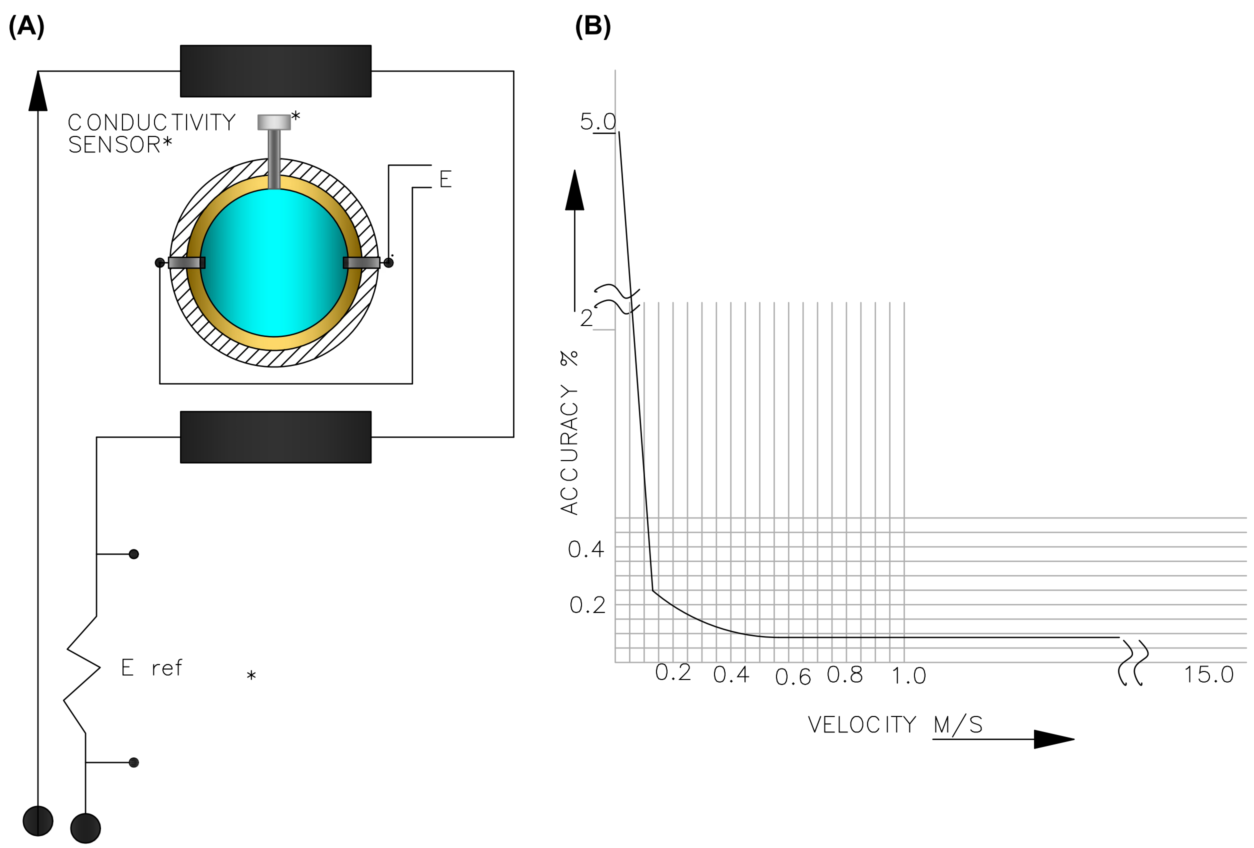


FIGURE V/5.1.4-1 EM flow meter performance. (A) Meter K factor and conductivity sensor. Conductivity sensor used for empty pipe detection, refer to Section 5.1.5. (B) Accuracy versus velocity.

performance data for this meter. Here the best available data are shown but may not match with any particular meter specification. From the discussions it is clear that the velocity of flowing fluid has a direct impact on the induced voltage. In fact, the ratio of induced voltage and velocity gives the sensitivity of the meter. Thus as the velocity decreases, the error percentage increases and at very low velocity sensing will be difficult. For this Fig. V/5.1.4-1B may be referenced. In Fig. V/5.1.4-1B the focus is on the nonlinear part of the curve. It can be seen that below 0.5 m/S velocity accuracy is nonlinear, as well as being quite high. Above the same level the typical accuracy is around 0.2%. Again the achievable accuracy with dual-frequency excitation may be better and for standard excitations an additional 1 mm/s may have to be added.

- *Overall accuracy:* ~0.2% AR; normally the pulse output accuracy will be better and for analog output around 0.05% FSD may be added.
- *Repeatability:* 0.1% AR (v > 1 m/s); 0.05% AR (v < 1 m/s).
- *Sensitivity:* Typical sensitivity is 150–200 μV/(m/s).
- *Velocity range and voltage developed:* Velocity range is 0.5–15 m/s. Typical induced voltage in this velocity range is 75 μV to 6 mV. (***These are not specific direct performance data but are indicated here for reader to get idea.***)
- *Temperature effect:* 0.08% AR/10°C for analog output additional effect to be considered.
- *Turndown ratio:* In the electromagnetic flow meter for a given flow rate, a different velocity could be selected to get a different size. Turndown ratio of >100: 1 is possible in practice.
- *Response time:* 100–200 ms.

5.1.5 EMPTY PIPE DETECTION

Empty pipe detection is important for electromagnetic flow meters because, when electrodes are not in contact with fluid it is open and on account of high resistance it is susceptible to coupling stray voltages and interference from surroundings, thus making an error in rate flow as well as totalizing flow. In order to prevent false readings/totalizing this is used as an alarm as well as for control function. It is also used to detect the standby process line. There are a number of methods which could be adapted for detection of empty pipe detection. In fact, some of these method can also detect partial filling of the pipe. At times these are advantageous, but in some cases it is problematic also. Some methods of detections are described here.

1. **Additional probe type:** An additional electrode/conductivity probe is mounted on top of the pipe for sensing the resistance/conductivity as shown in Fig. V/5.1.4-1A. When the medium is below the sensor the due to partial filling of the pipe, the resistance increases to generate alarm. Here the switching point should be set below the lowest electrical conductivity that can occur in the process. A major advantage of an additional full pipe electrode is the early indication of a partially filled measuring tube even before emptying the tube. During filling or emptying the pipeline fluids are not measured and totalized until the pipe is fully filled or emptied again. The response of the probe for highly viscous process liquids, incrustations, or gas collected at the top and coating sludge are either very slow or very poor [29]. From here alarms are activated as the pipe is not full.
2. **Change in resistance:** This method is applicable for galvanic measurement. For a pipe filled with conductive process fluid, measurement electrodes are connected through the process fluid and have much less resistance compared to when the pipe is empty. Thus the change is resistance indicates the empty pipe. The main advantage of this system is that there is no additional expense towards additional hardware. However, problems with it are that:
   - It will give a false reading in case of vertical installation, especially for long pipes, because of dripping fluid even when it is empty;
   - it will give a false reading when there is a coating built up on the probe.
3. **High-frequency signal:** Flow measurement is normally carried out by a low-frequency signal, so a high-frequency current generator across the flow meter sensing probes could be used to detect the conductivity. This high-frequency signal is ignored by the flow signal amplifier [5].
4. **Flow profile test:** When a pipeline is partially filled the flow profile is asymmetrical. There is less process liquid flowing in the upper part of the measuring tube than in the lower part. This can be detected through the associated electronics of the signal converter, disregarding electrical conductivity, viscosity, and incrustations. This flow profile test only responds when the liquid level has sunk below a value of about 75% [29].
5. **Discussion:** Empty pipe detection can be used as an alarm or as a control to start/stop the pump and/or open or close the valve. As stated earlier, this can be used for standby operation as discussed above. However, there are cases when false signals/alarms are generated, which should be bypassed by judicially looking into the problem.

5.2.0 Features and Applications of Electromagnetic Flow Meters

Prior to going into the details of meter design, sizing, and selection it is better to get some idea about the features and application areas for electromagnetic flow meters.

5.2.1 FEATURES OF ELECTROMAGNETIC FLOW METERS

The various advantages and disadvantages of electromagnetic flow meters are discussed here.

1. **Advantages:** The following are the major advantages of the flow meter.
   - Electromagnetic flow meters (being nonintrusive) do not offer any obstruction to the flow path and have no moving parts.
   - Pressure loss in the flow meter is negligible—the same as that in a pipe of meter length.
   - Electromagnetics can be used for bidirectional flow measurement.
   - With the wide range of materials available for lining, the meter can be used for almost all liquids including corrosive materials. The lining offers both insulation as well as corrosion abrasion resistance.
   - On account of resistance of the liner against abrasion, electromagnetic flow meters find their use in slurry applications. Also, obstruction-less flow passage is helpful for slurry and so it is used for wood pulp, sewage, and mud, etc.
   - The electromagnetic flow meter is not much affected by density and viscosity.
   - There is not much impact of upstream straight length on an electromagnetic flow meter.
   - Except for old AC excitation systems, the power requirements of electromagnetic flow are nominal at around 15−20 W.
   - Magnetic flow meters are available in a wide variety of line sizes and flow ranges.
2. **Disadvantages:** The following are the major limitations to the flow meter.
   - For functioning of the meter the fluid should be conductive on account of its very low conductivity. Pure substances, hydrocarbons, petroleum products, and gases are not measured with this meter.
   - The reactive resistance of the liquid between the electrodes should not exceed 1% of the impedance of the external circuit [30].
   - Electromagnetic flow meters are relatively heavy, especially for large sizes.
   - Electromagnetic flow meters are slightly expensive.
   - To avoid the problem of entrapped air in horizontal installation, the electrodes should be on the horizontal diameter at the place where induction is maximum.
   - Zero check for the flow meter cannot be done online without stopping the meter and essentially needs a block valve to be installed for this purpose.
   - Empty pipe detection is done to avoid errors in measurement.
   - It is not suitable for very low fluid velocity as accuracy suffers.
   - Electrical installation of the meter needs special care.
   - Electromagnetic flow meters have limitations in use for the fluid with magnetic properties (liquid with suspended metal), due to magnetohydrodynamics (MHD), which refers to change of flow pattern under the influence of a magnetic field.

5.2.2 APPLICATION AREAS OF ELECTROMAGNETIC FLOW METERS

The following are the major application areas for this meter.

- Electromagnetic flow meters are primarily considered for almost all kinds of liquid with minimum conductivity. As stated earlier, on account of the wide range of liner materials it can be used for corrosive and abrasive liquids, including slurries.
- They are suitable for almost all industrial fluids except gases and petroleum products with low electrical conductivity.
- They are extensively used in pulp and paper plants, effluent treatment plants, as well as flow measurement of non-Newtonian fluids.
- For applications, proper sizing and judicious comparison of its simplicity, highly precise and reproducible output (with cost) to be weighed against magnetohydrodynamic effect.

5.3.0 Part Details and Design Aspects of Electromagnetic Flow Meters

There are a number of design issues related to the electromagnetic flow meter. In the following discussions various part details, along with design

aspects, shall be discussed in brief. The discussions start with electrodes for flow measurement.

5.3.1 ELECTRODES AND ASSOCIATED DESIGN ISSUES

There are two different methods of measuring induced voltage: galvanic and capacitive types. The galvanic type is used in the majority of cases and is in contact with the fluid. Therefore, major design issues are connected with this. In this section some of these issues will be touched upon. Unless stated specifically these issues are meant for galvanic type electrodes. Sealing and electrode coating are major design issues of galvanic type electrodes. The discussion starts with Fig. V/5.3.1-1A.

1. **Sealing and holding:** One of the main concerns is the need to ensure that there is no leakage of the process medium. The electrodes are sealed with a proper sealing. Normally, four to five separate sealing surfaces and a coil spring are used for this purpose. The coil spring is used to force the electrode to just protrude inside the meter or flush with liner as shown in Fig. V/5.3.1-1A. Sealing is done where the electrode is coming out of the meter. In some cases, where there is a chance of electrode erosion, and there is need for quick replacement, field-replaceable electrodes are used. In order to ensure that the overall integrity of the system is maintained, even if a process leak should occur past the liner/electrode interface, the electrode compartment can also be separately sealed [5]. Electrodes are held in position by a spring in the electrode holder. There are a few designs with a flush electrode with no exposed seal suitable for slurry applications, e.g., ADMAG of YEL.
2. **Electrode coating:** It is always intended to avoid any kind of coating on the electrode to maintain the flow-measuring accuracy. However, for measuring fluid flow in slurries, resins, and soap, etc. such coating formation is difficult to avoid, the coatings may be abrasive and damage electrodes. Electrode coatings are associated with galvanic measurement of flow. When the conductivity of the coating is greater than the fluid, the result is a flow signal representing less than actual flow [31].

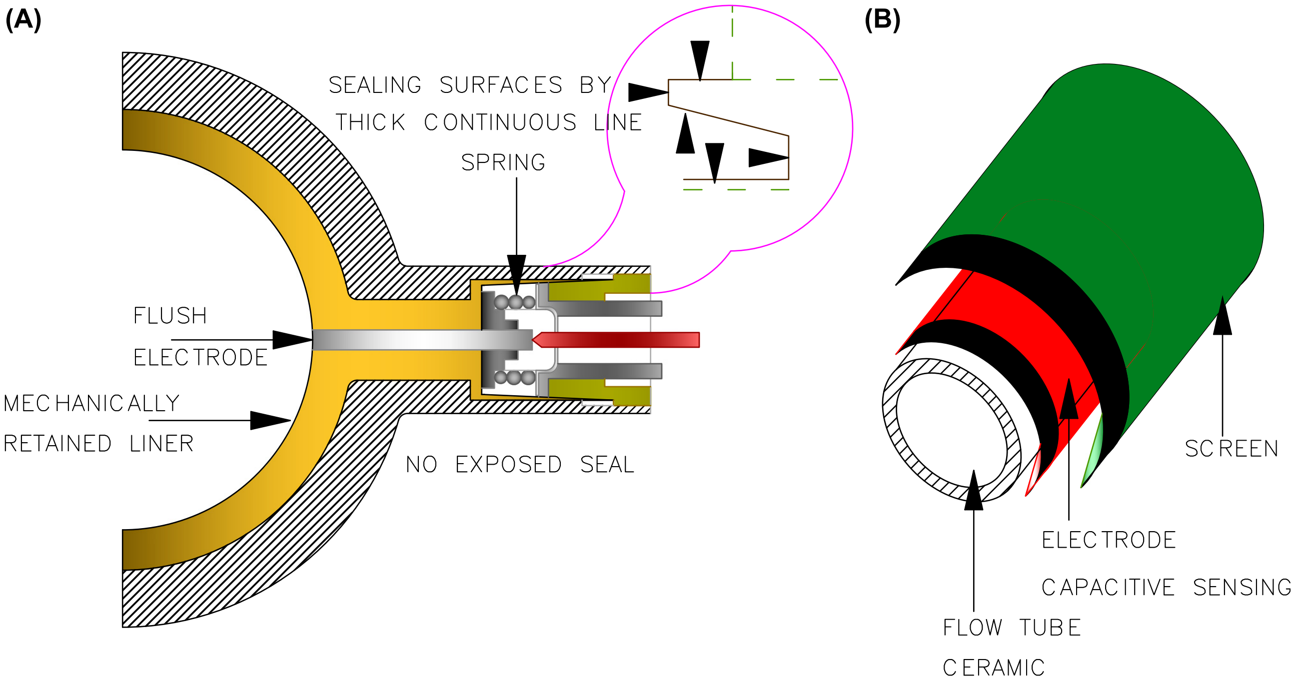


FIGURE V/5.3.1-1 Electrode details. (A) Galvanic electrode details. (B) Capacitive electrode details. *Developed based on ADMAG electrode. Courtesy: Yokogawa.*

However, the opposite is not true always, because initially such a case may show higher flow but later it becomes unpredictable. Several approaches are adapted to overcoming this.

- *Optimum flow velocity approach:* When the velocity of a fluid with suspended materials is high then the chances of settlement will be less, also there could be a scrubbing effect. The important issue here is to consider and balance the chances of wear of the liner if there is presence of abrasive material.
- *Flow profile approach:* Turbulence is altered through the use of a flow conditioner, but there is the chance of wear of the liner with abrasive materials in this method.
- *Retained liner:* Some designs, like that in ADMAG of YEL, use a retained liner and an insertion style electrode. Here abrasion may be less and as the sealing surface is not exposed to process material the electrode life is increased. Also, it reduces slurry noise [32].

3. **Electrode for capacitive measurement:** Short discussions on measurement with capacitive types of sensors have been discussed in Subsection 5.0.3.2. As stated there, the capacitance probe is created by a metal area electrode. These electrodes cannot be exposed without a shield because there will be noise pickups. Proper screening for this is necessary, which is detailed in Fig. V/5.3.1-1B.

5.3.2 MAGNETIC FIELD AND FIELD EXCITATIONS DISCUSSIONS

From Section 5.0.5 readers have a fairly good idea about the field excitation and magnetic field necessary for the meter to function. There are three main types of excitation systems common to electromagnetic flow meters. In this section these will be discussed.

1. **Pulsed DC field:** The type of field excitation shown in Fig. V/5.3.2-1A is used in most modern electromagnetic flow meters. This type of excitation system eliminates electrochemical voltage, quadrature voltage, and other noises associated with AC field excitation systems discussed later. Firstly we look into the functioning of the system.

- At T_0 DC power is applied to the field coil. Since this is an inductor, it will take some time to charge, i.e., to reach the final value at T_1. When there is reversal of excitation, the inductor cannot immediately respond. Therefore, after decay, the excitation current and flux will remain constant
- $\frac{d\varnothing}{dt} = 0$ as result the transformer action disappears and also capacitance noise is less.
- At T_1 the transmitter is turned ON for a while between T_1 and T_2 (which is 20 ms for Hz and 16.66 ms for 60 Hz). This is to eliminate line potential—an external noise. The signal generated at this interval (I_1)

$$E_1 = E + E_{noise}. \qquad \text{(V/5.3.2-1)}$$

The value is stored. At T_2 polarity is reversed. The same phenomenon as described above will occur in the opposite direction (I_2). So,

$$E_2 = -E + E_{noise}. \qquad \text{(V/5.3.2-2)}$$

- The transmitter subtracts values at I_2 from I_1.
- The resultant $= E_1 - E_2 = E + E_{noise} - (-) E - E_{noise} = 2E$, which is free from noise and is proportional to the volume flow rate. In pulsed DC-type systems, zero is established during each on−off cycle and it is also known as the automatic zero adjusting system.

The system provides the following benefits:

- Normal conductivity lower limit is 5 μs/cm;
- Stable zero, i.e., inherent zero compensation; auto zeroing;
- For the above reason it is possible to extract a signal even with zero shift [9];
- Simplified installation system;
- Larger insulating coating can be tolerated, hence lower conductivity limit;
- It has much lower power requirement.

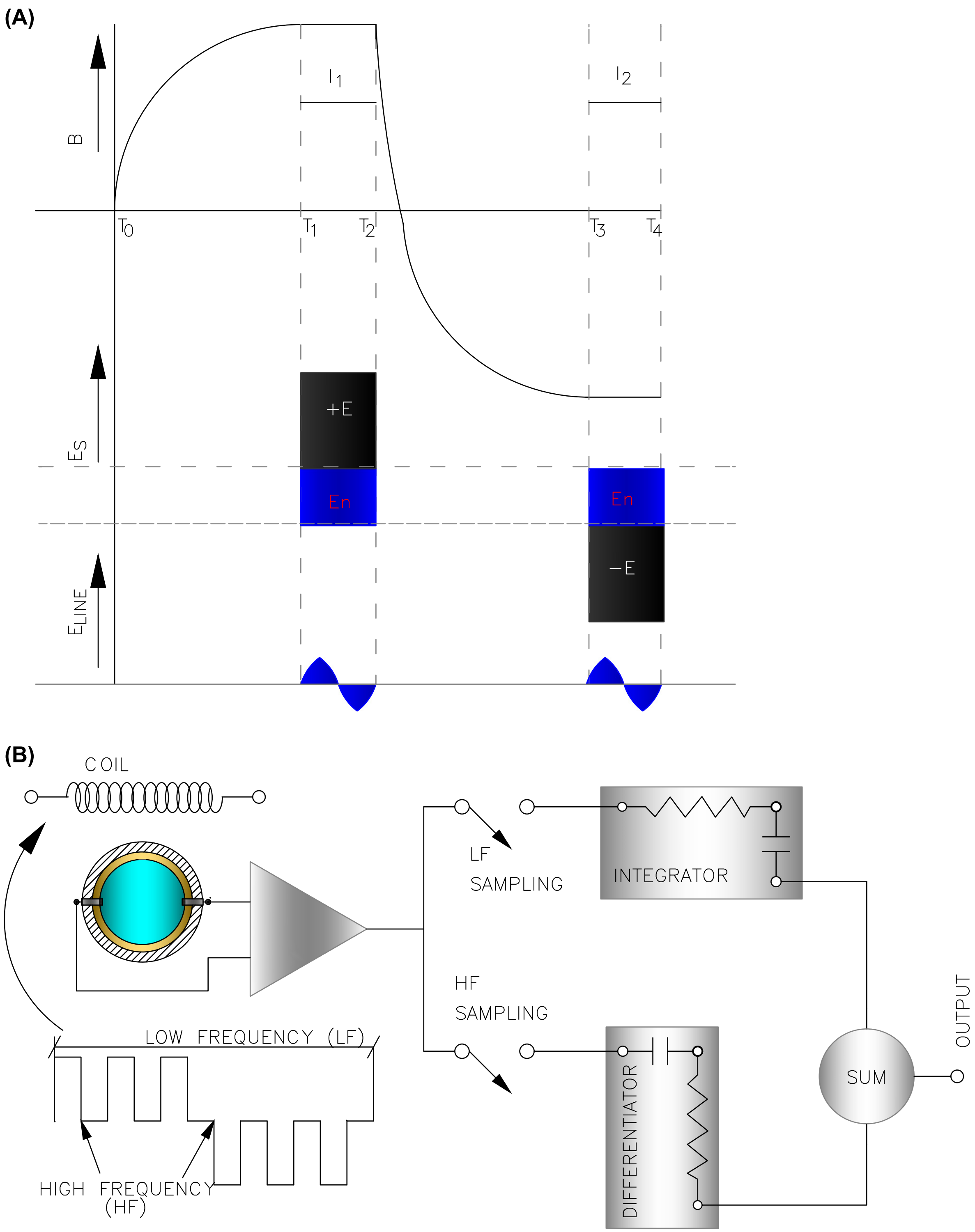


FIGURE V/5.3.2-1 Field excitation systems. (A) Pulsed DC field excitation. (B) Double-frequency field excitation.

However, there are a few issues that need to be addressed in this system and these could be considered as limitations, e.g.:

- Polarization/electrochemical/electromechanical effects;
- Slower response, hence not suitable for flow with rapid changes;
- With the use of higher frequency of sampling some issues may be addressed but there will be prominent transformer noise.

2. **AC field excitation:** There are magnetic flow meters which use AC at mains frequency (50 or 60 Hz) for magnetic field generation in the coil to induce voltage for flow measurement electromagnetic flow meters. The magnetic field intensity produced and the voltage induced at the electrodes are also sinusoidal and induced voltage is proportional to fluid velocity. The undesired electrochemical voltage variations are slow to be filtered out. However, when there is a line voltage variation it will affect the induced voltage accordingly. There is another voltage induced in the system due to the loop formed by electrodes, lead wires, and fluid medium. This voltage is proportional to the rate of change of magnetic strength. Since these are developed at 90 degrees out of phase this voltage is referred to as quadrature voltage and is eliminated by synchronous demodulation at the transmitter. However for AC excitation systems a wide range of frequency signal between 10 and 5000 Hz (400 Hz common) is available. High-frequency signals are often used for pulsating flow but can give rise to skin effect (skin effect is a tendency for alternating current to flow mostly through the outer surface of an electrical conductor and the effect increases with the frequency of AC signal) to cause error so is not required for fluid with high conductivity. In the case of an AC excitation system the polarization effect is reduced and is capacitively decoupled. The measuring voltage E is in phase with Φ, but because of high inductance of the coil, the magnetic flux Ø lags the excitation current by almost 90 degrees. Many AC noise voltages (as mentioned earlier, e.g., quadrature voltage), are not in phase with the measuring voltage E. Phase-selective circuits could be used to eliminate them [1]. External noise voltage and phases are unpredictable, so, *those in phase* with the signal can make the zero *unstable*. To a certain extent, zero adjustments can be compensated for by actual measurement, e.g., with the shutoff valve closed, zero command is given to the meter for zero correction. Therefore, periodic rezeroing may be necessary to get an accurate output. To avoid the effects of noise and fluctuations, special cabling and calibration practices recommended by the manufacturers must be used to ensure accurate operations. Normal conductivity of fluid is 20 μs/cm but this can be further reduced with the help of an impedance converter. Another positive side of an AC electromagnetic flow meter is that it has *less* impact on performance due to changes in flow profile. AC electromagnetic flow meters find their application in filling machines, medical uses, and miniaturized flow meters.
3. **Dual-frequency excitation:** From the discussions on pulsed DC systems one good thing is that it has stable zero, as well as good noise rejection, but has a slow response. On the contrary, if high frequency is used the response time will be improved. In the dual-excitation system shown in Fig. V/5.3.2-1B there are two parts to the circuit. Low-frequency waveform to guarantee zero stability is further integrated via a low-pass filter with long time constant and a smooth and stable output signal. The high-frequency part is processed in a differentiating circuit with the same time constant. The high-frequency carrier is superimposed on the low-frequency signal for better immunity to noise for low conductivity and slurries, and electrochemical reactions [9].

The two components are added together to get the output. Further details on dual-frequency excitation are available in Section 3.1.4 of Chapter VII. Also, for other *ways and means* of eliminating slurry and other noise, by adapting selective excitation frequency, Section 4.4.4 and Table VII/4.4.4-1 of Chapter VII may be referenced.

5.3.3 ELECTROMAGNETIC FLOW METER GROUNDING

Not only for accurate flow measurement, but also in some cases for the safety of personnel, grounding is mandatory. This is basically an exercise to be carried out as a part of installation. Irrespective of the process pipe material, grounding is essential to reduce interfering stray current/voltage which could affect the flow measurement. The flow meter sensor must be connected to ground potential, and this potential should be identical to the potential of the metering fluid. Usually suitable straps/rings/plates are used for grounding. Flange bolts should be used as grounding bond because rust and other material may cause insulation between the flange and bolts. In case of nonconducting pipelines or in case of insulation, ground plates at both ends of the electrode are used. Improper grounding will result in zero offset and/or signal drift. It is important to follow the manufacturer's recommendations as the manufacturer has the maximum experience with the product. In the case of remote transmitter connection it is important to ensure that there is not much potential difference between the meter with the transmitter. It is important to have proper *bonding* of the flow meter to the adjacent piping to minimize zero shifts [9]. Manufacturers often supply and always recommend to have a copper braided jumper between the meter flange and pipe flange. Therefore there are several possible methods available to ensure equipotential bonding. These shall include but not limited to the following and have been depicted in Fig. V/5.3.3-1.

1. Grounding in pipelines that are electrically conductive inside. However, there are applications where it is not possible to carry out a traditional grounding connection to adjacent piping and to earth ground.
2. Grounding using grounding rings or discs used for pipelines made of plastic, concrete, or piping with an insulated lining. Ground rings are recommended over ground electrodes in the following situations [33]:
   - The fluid conductivity is less than 50 μs/cm;
   - Wafer-style flow tubes installed in nonconductive piping or lined piping;
   - Electrolytic process applications (described in the next section)
3. Grounding using a grounding electrode. There are several methods that all have the same objective. One way could be to directly connect the grounding electrode in the tube to the grounded housing of the primary head, but this could cause serious damage to the electrode if there exists some potential difference [32].
4. **New grounding methods:** There are new grounding methods where grounding of process liquid is not done on the primary head. These methods are [32]:
   - Floating grounding electrode to transfer the reference potential of the process liquid;
   - Virtual grounding (virtual reference)—see Ref. [32].

Also, for any AC equipment, as per the local electricity rule, it is necessary to have suitable grounding of the device with green wire, so the importance and necessity of grounding for electromagnetic flow meters cannot be overestimated.

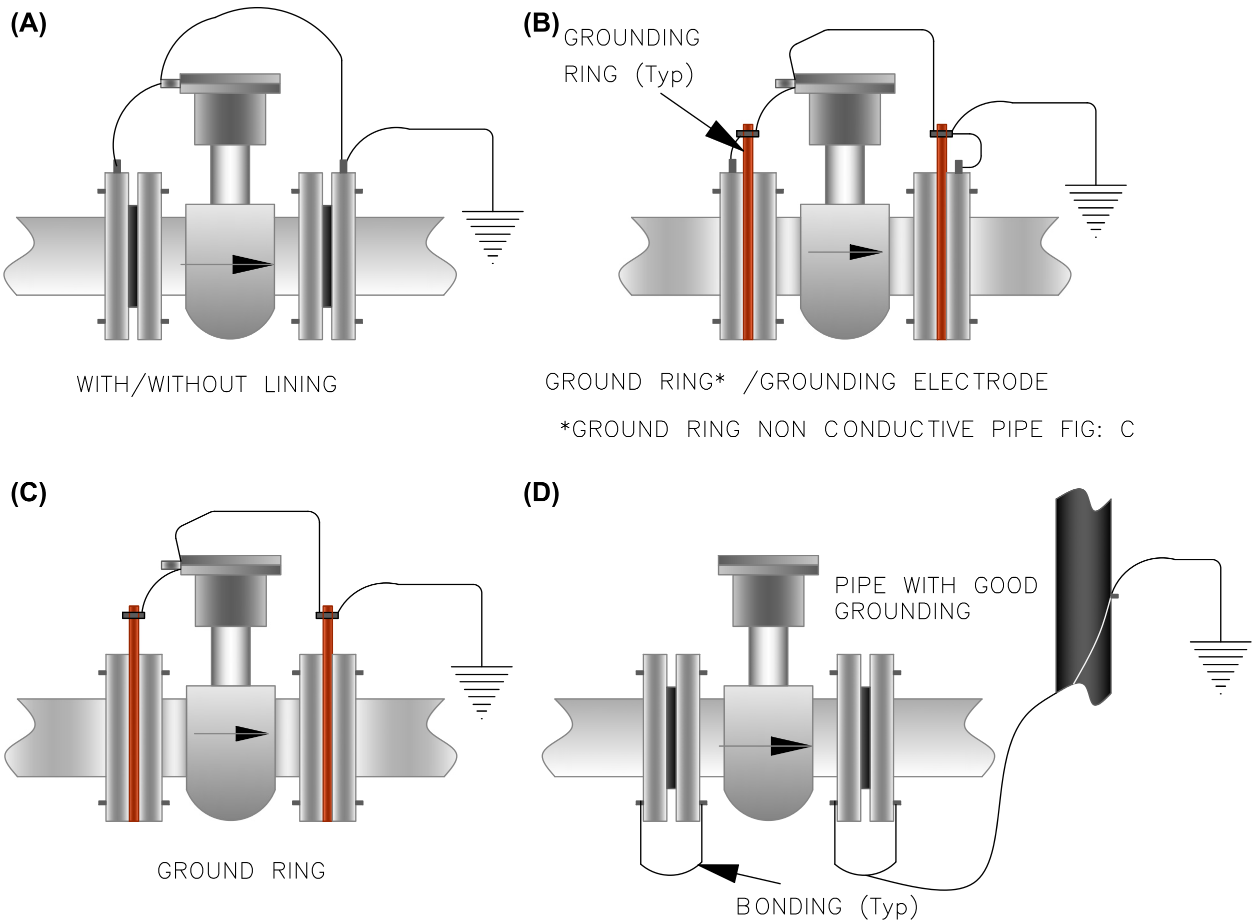


FIGURE V/5.3.3-1 Grounding of electromagnetic flow meter. (A) Conductive pipe. (B) Nonconductive/conductive lined pipe. (C) Nonconductive pipe. (D) Nearest pipe grounding.

5.3.4 NOISE AND ELECTRONIC DESIGN IMPROVEMENTS

In this section short discussions on types of noises and improvement of electromagnetic flow meter design with digital signal processing shall be touched upon.

1. **Noise:** The major challenge faced in flow measurement by electromagnetic flow meters is very small induced voltage developed at electrodes due to flow. Therefore, there is every possibility that this induced voltage is distorted by an external interfering signal. These extraneous signals can collectively be called noise. The noise issues for the meter have already been covered in Section 5.0.6, which should be read in conjunction with this section. The major sources of these noises include the following:
   - *Electrochemical emf:* Developed due to the electrolytic reaction between the metal electrode and the ion-conducting process fluid;
   - *Quadrature voltage:* Developed due to inductive coupling AC designs, occurring with any conductor located within the magnetic field;
   - *Electrode circuit voltage:* Developed due to capacitive coupling with the coil excitation circuits or other power circuits;

- *Transmission loss:* This loss occurs in the circuit as a result of lead resistance as well as stray capacitance of the cables;
- *Current loop:* There could be stray voltages or current loops developed within the process fluid.

2. **Design improvements:** There have been considerable investments in terms of time, money, and labor to reduce the noise effects and improve the performance of the meter. As a result, over several years the performance of electromagnetic flow meters has improved quite significantly. Advances in digital signal processing (DSP) and development of ways and means to reduce noise have made it possible to achieve improved performance by the meter. Some of these advancements are covered in the following.
   - *Analog signal processing:* In conventional systems there is a preamplifier stage with a high input impedance and high common mode rejection. Post preamplifier there would be some bandpass filter sample and hold circuit before the output is fed to ADC. In modern systems the oversampled approach consisting of a single stage greatly simplifies the analog frontend design and pushes the performance requirement of the ADC block [34].
   - *The magnetic field:* The magnetic excitation is done with the help of a number of switches in the H bridge and the same is controlled by a dedicated microprocessor.
   - *Sensor driver stage:* The sensor driver stage gives significant area benefits when compared with Opto couplers (in a conventional system), which are not very reliable.

We now address another important electrical device transmitter which is also responsible for the performance of the metering system.

5.3.5 SECONDARY DEVICE (TRANSMITTER)

In this section short discussions are given on transmitters. Sensor details have already been covered above. The signal generated at the electrode of the electromagnetic flow meter is a feeble signal which cannot be handled and cannot be transmitted unless it is converted and processed. So the basic functions of the transmitter include but are not limited to conversion, processing, and transmission. In modern transmitters there are additional functions like diagnostics, autoranging/checking, superimposition of digital signal with analog output, and/or fieldbus communication, etc. With the provision of transmitters with local display an alarm units, transmitters also need to manage this indication alarm and control (empty pipe detection) functions also. Based on the housing arrangement there are two transmitter variants, i.e., remote mounted and integral mounted transmitters. These are detailed in Fig. V/5.3.5-1. When the environment at the field location (point of measurement) is not conducive, remote transmitters are often preferred for convenience, flexibility, and a more benign environment. There are variations of transmitter accuracy with distance, and many manufacturers offer a special cable between the flow tube and transmitter. This is necessary to protect the very weak signal of the flow tube from internal and external interfering signals. The maximum distance between the transmitter and flow tube is a function of the meter design, fluid conductivity, and field excitation. Therefore this is guided by the manufacturer's data.

A distance of 30 m between the flow tube and remote transmitter is not uncommon. Pulse and analog outputs of 4–20 mADC are commonly available in conventional electromagnetic transmitters. Modern transmitters also support HART protocol and various fieldbus systems (discussed in a consolidated manner in Section 8.0.0 of Chapter XI and Appendix VII). Normally the transmitter is provided with a local flow indicator, totalizer with LCD/LED display, and operating buttons (for alarm/control setting, reset).

Therefore, the major functions of an electromagnetic flow transmitter include the following:

1. Amplify, process, and transmit the flow signal generated by the sensor;

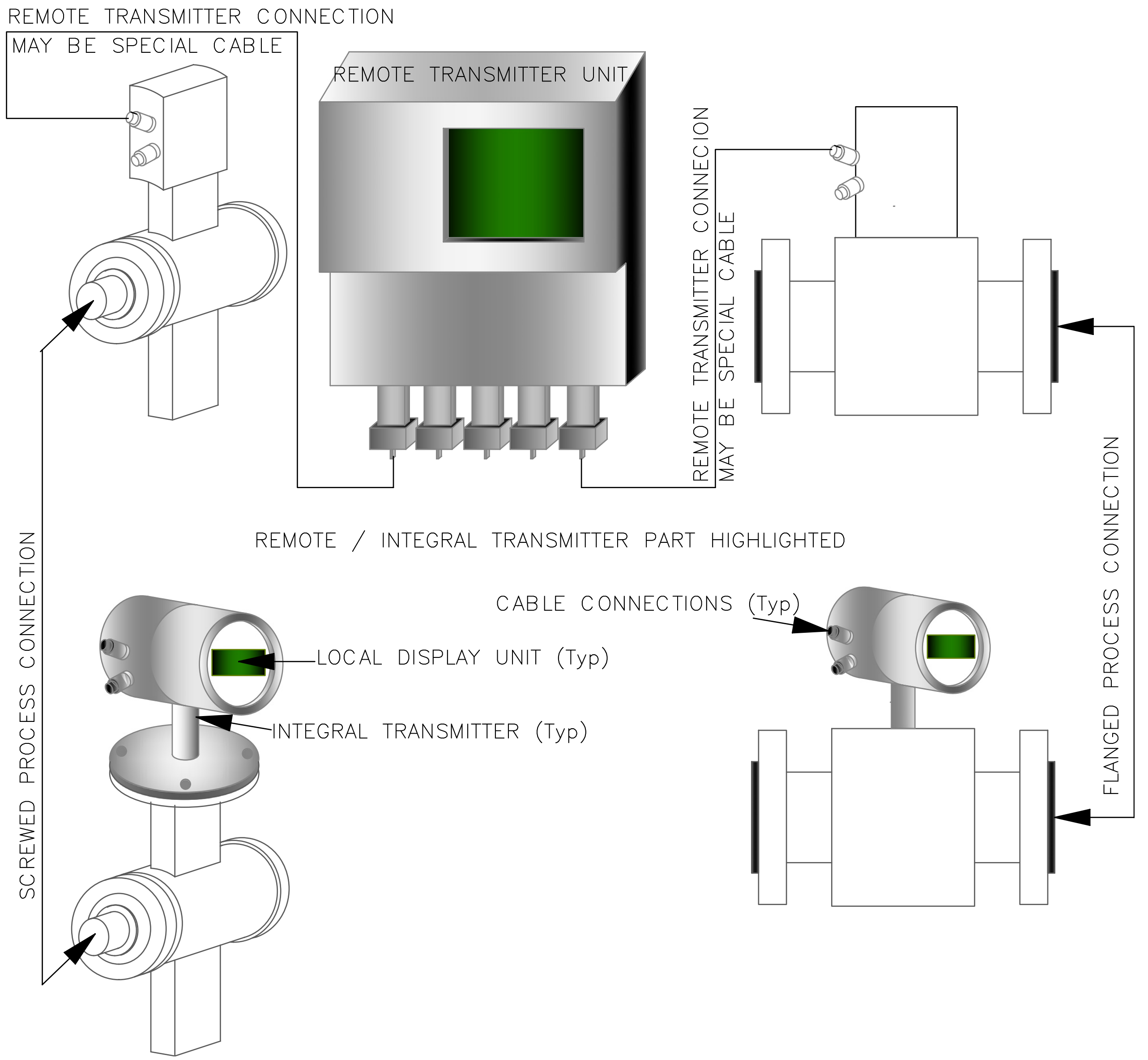


FIGURE V/5.3.5-1 Electromagnetic flow meter and transmitter.

2. To ensure the transmitter is insensitive to power supply changes and radio frequency (and other) interferences;
3. Transmitters also have functions to support local indications of rate flow;
4. Transmitters also perform totalizing and some control functions;
5. Modern transmitters meet the requirements of safety and diagnostics;
6. Modern transmitters support secondary instrument calibration through a handheld calibrator;
7. Modern transmitters have fieldbus communication capability (Ref:Appendix VII);
8. **Secondary electronics discussions:** At present almost all meters are smart meters. These meters use microprocessor-based embedded electronics—microcontrollers/DSP not only for regulation purposes, but also for driving outputs and communications, self-diagnostics, operator interface, etc. Therefore it is necessary to program the meters prior to start up. A typical block diagram of transmitters/converter has been depicted in Fig. V/5.3.5-2. In the case of

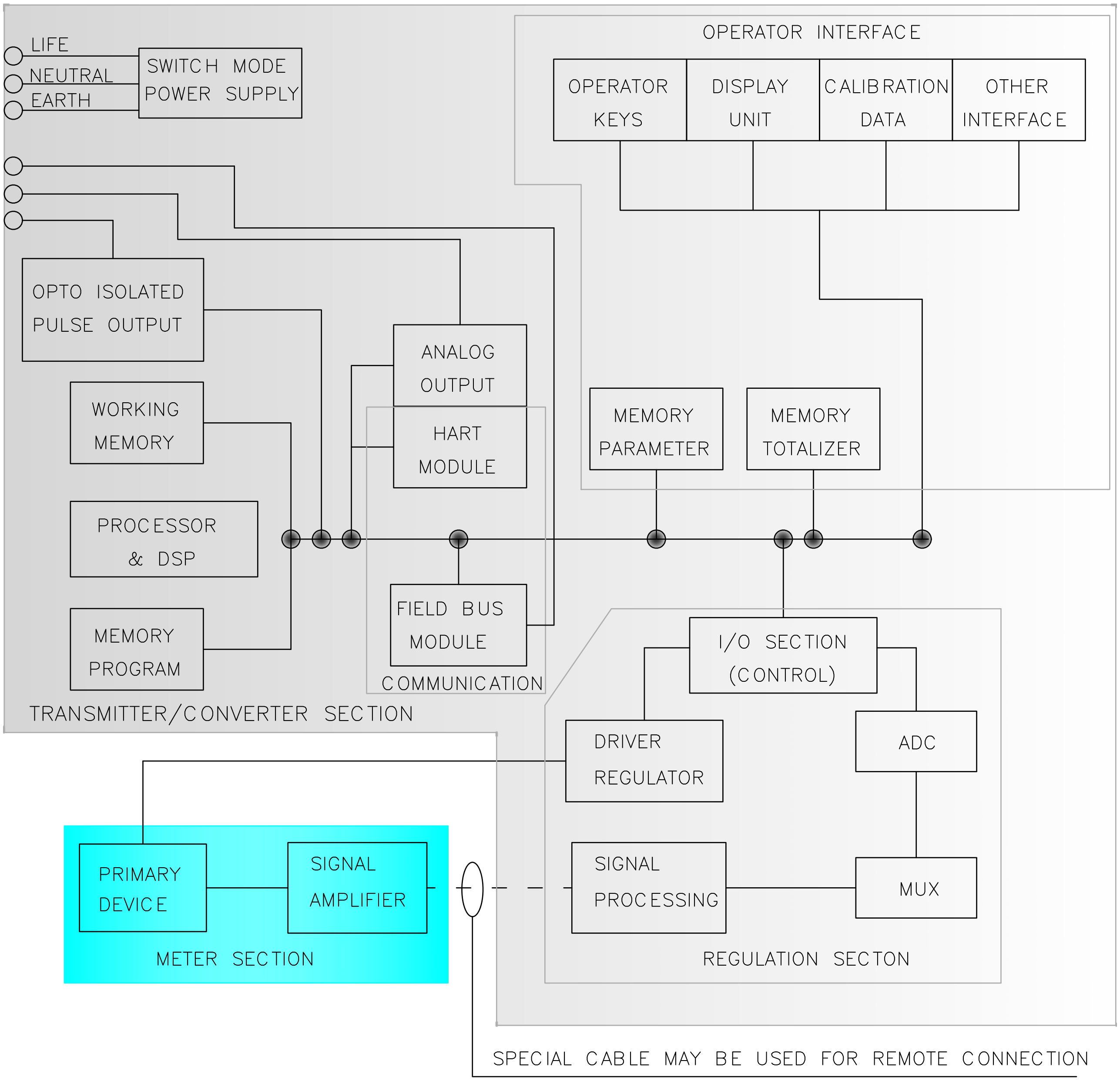


FIGURE V/5.3.5-2 Electromagnetic flow meter electronics (typical). For abbreviations see list of abbreviations at the end of the chapter.

remote electronics a special cable may be insisted upon by the manufacturers. The block diagram presented here is based on the author's experience (with ABB COPA electromagnetic flow meter), and is a typical one although it may vary with other meters. However, the basic building blocks will be more or less the same. Here another important issue is *empty pipe detection*. This facility is not present in all electromagnetic flow meters, and hence is not shown in this figure. The empty pipe detection module where present is normally connected with a preamplifying stage in the metering section and generates alarms/control through secondary electronics, i.e., through the transmitter section.

5.3.6 FLOW RANGES, METER SIZING, AND SELECTION

As a rule of thumb normally flow meter size is selected as a nominal diameter of the pipeline, such as NB 40 or DN25. However, this is an extremely crude method of selection and cannot be applied generally. Each manufacturer, based on their design, specifies a flow range chart in which they specify the minimum and maximum flow range possible for the respective meter.

Velocity consideration: A typical chart has been presented as Table V/5.3.6-1. Prior to moving to the table a few issues are explained. The second column shows the minimum flow range possible. Naturally, the question of the velocity is raised. The same applies for the maximum range mentioned in the next column. From this one can infer that the minimum and maximum possible velocity actually decide the minimum and maximum flow ranges. Looking back to Fig. V/5.1.4-1B and discussions in Subsection 5.1.4.2 one can notice that through velocity, the meter accuracy is also interlined. From the discussions presented so far it is clear that a proper selection of velocity is important not only for flow range selection but also for accuracy. Velocity range from 0.5 to 10 m/s is the normally acceptable range of velocity. However, for normal liquid applications, 2–4 m/s is mostly chosen. However, for liquid with solids higher velocity is often chosen to avoid settlement of solids on electrodes.

Flow range table: For an application the flow rate is guided by the process and one has to select a meter size (keeping in mind the line size) and ensure that the flow rate of the medium lies between the minimum and maximum full-scale ranges of the specific meter. An important issue here is that the table shows the minimum flow range and NOT the minimum flow value. The same is the case for maximum flow range. Suppose an application calls for 25 LPM flow, so one can select a meter size ½″ NB/DN15 as the flow value exceeds the minimum flow range and is within the maximum flow range. The flow rate nomograph (Fig. V/5.3.6-1) discussed later will be required to reach the velocity and get the associated accuracy from Fig. V/5.1.4-1. It is worth noting that for a good meter 100:1 turndown in flow *range* is possible.

Flow rate nomograph Fig. V/5.3.6-1: If the above discussion is continued, it can be seen that the application data are cross-checked with the minimum and maximum flow ranges to see that for a particular size it is within the range.

TABLE V/5.3.6-1 EMFM Flow Meter Size and Flow Range

Meter Size		Min. Flow Range (0.5 m/s Velocity)		Max. Flow Range (10 m/s Velocity)			Pressure
DN	ANSI	LPM	GPM	LPM	GPM	Flange Material	Rating–PN (Bar)
10	3/8	0–2.25	0.6	0–45	0–12	SS316 Ti	40
15	½	0–10.8	0–0.29	0–108	0–29	SS316 Ti	40
25	1	0–10	0–2.6	0–200	0–53	SS316 Ti	40
50	2	0–50	0–0.8	0–1000	16	SS316 Ti	40
100	4	0–46.66	0–12.33	0–4666	1233	SS316 Ti	16 or 40
200	8	0–900	0–14.3	0–18000	0–1430	SS316 Ti	10,16,25,40
400	16	0–3750	0–59.4	0–75000	01,188	SS316 Ti	10,16,25
800	32	0–15000	0–238	0–300000	0–4760	SS316 Ti	10,16

DN sizes are in SI (mm) and ANSI in inches. For equivalence of PN rating with ANSI, Fig. V/1.0.0-1 may be referenced. The last two columns have been included to chart data in one place and in many manufacturers' data these two columns may be missing. Data presented here are from some reputed manufacturers, but will not match with any single particular manufacturer.

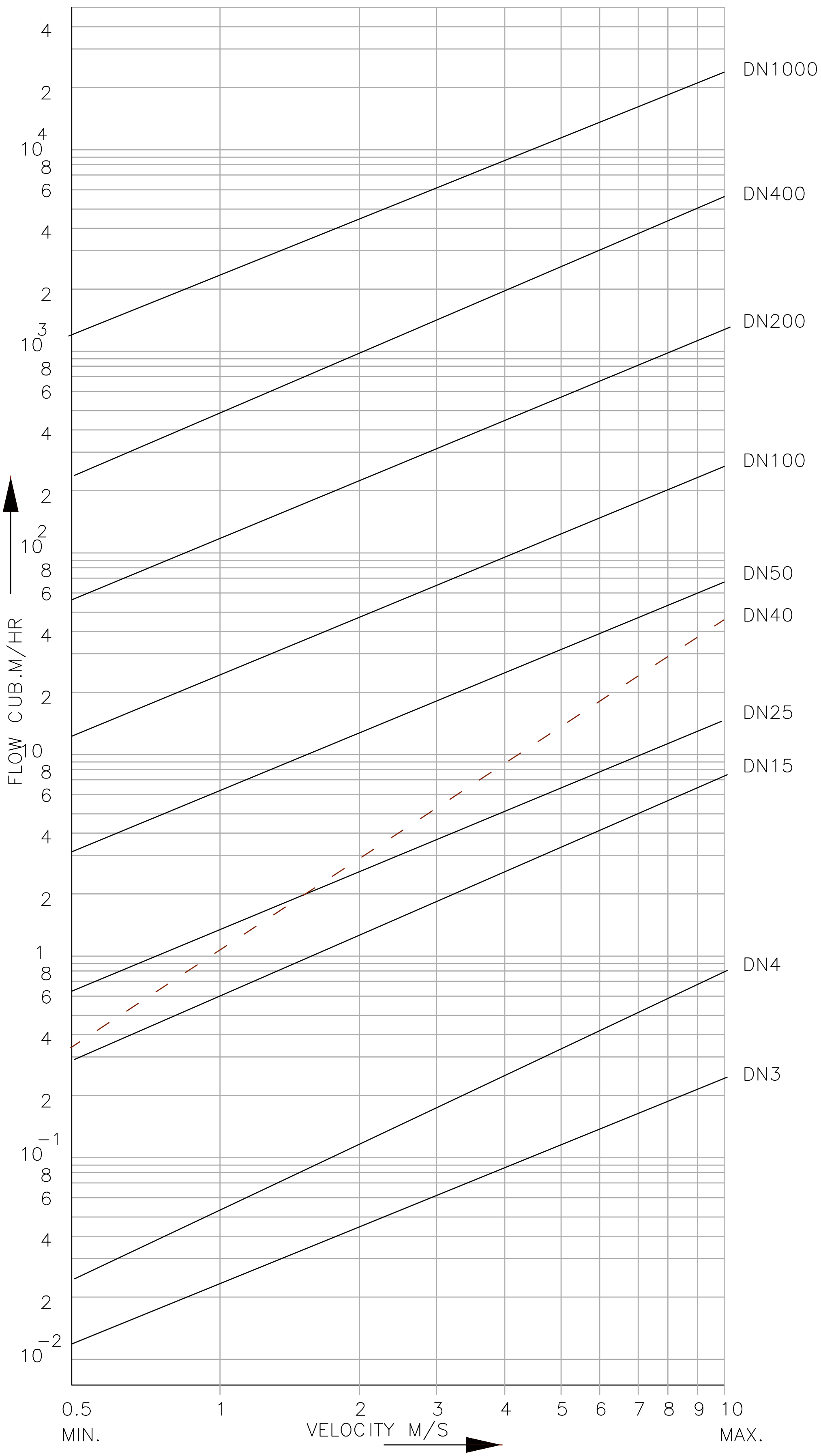


FIGURE V/5.3.6-1 Flow rate nomograph. *Dotted line* belongs to other manufacturer. Hence there is possible crossing of lines. *Developed based on data from one reputed manufacturer shown by continuous lines. Dotted line belongs to other manufacturer. Hence there is possble crossing of lines.*

The volumetric flow rate is a function of both the flow velocity and the flow meter size.

To ensure that for the selected size of the meter the velocity is in the desired velocity range, one can use the flow rate nomograph shown in Fig. V/5.3.6-1.One has to select the meters which have sizes that cater to the given data with maximum values with the minimum (0.5 m/s) to maximum range (10 m/s). In that range one would get a number of sizes. From there one has to select the one which matches the desired velocity (in the previously discussed example of 25 LPM will be around 2.5 m/s velocity which will be in good accuracy range in Fig. V/5.1.4-1). This issue is self-explanatory. Note that here the graphs have been developed based on data from a reputed manufacturer. The graph lines are shown by thick continuous lines and none of them cross each other (they are not supposed to be crossing). Now there is another graph line shown by a dotted line which crosses DN25 lines—why? This is because the dotted line (intentionally kept dotted to show other manufacturer data) is a similar graphical line based on another manufacturer and so has a different gradient, etc. so that it crosses the DN25 lines. From this it can be inferred that based on the meter design there will be a different flow rate nomograph for each manufacturer and one needs to refer to the nomograph of the respective manufacturer.

5.3.7 MATERIAL SELECTION GUIDE

Material selection for an electromagnetic flow meter is an important issue. As already explained, this flow meter is used for almost all liquids, be they corrosive or abrasive, provided the measuring liquid has minimum electrical conductivity. During the discussions commonly used materials will be covered under different component headings. Since the liner protects the flow tube as well as insulating the electrode, its importance cannot be overestimated, so the discussion starts here.

1. **Liner material:** Table V/5.3.7-1 provides a list of materials with their characteristic features for some commonly used liner materials.

TABLE V/5.3.7-1 Commonly Used Liner Materials and Their Characteristics

Materials	CR	AR	T	P	Characteristics	Remarks
Soft rubber	F	E	70	64	For high slurry content	Inexpensive
Polyurethane	G	E	55	250	Erosion and wear resistance	Not used for strong acid/base
PFA	E	G	177	40	Resin with better shape	Food/beverage—US FDA
EPDM	G	VG	150	50	Excellent against weather aging	
PTFE	E	F	177	40	Excellent antistick. Less costly than PFA Most popular except slurry	Food/beverage—US FDA
Neoprene	G	VG	75	<100	Water/sea water use	
Hard rubber	G	F	~100	200	Wastewater/water	
Linatex	F	G		70	Mining slurry	With debris
ETFE	E	F	150		Similar to PTFE	More expensive
Elastomer	G	VG	130	70	Slurry	
Fused Al-Oxide	E	E	180	~50	For high corrosive and abrasive materials	

Al, aluminum; *AR*, abrasion resistance; *CR*, corrosion resistance; *E*, excellent; *F*, fair; *G*, good; *P*, pressure limit in bar; *T*, temperature limit in °C; *VG*, very good. PTFE and PFA are Teflon, difference comes from the resin used.

Often a PTFE lining is chosen because it is less costly, but they have a history of failure when a sudden vacuum is created due to pump or valve failure. There are various ways of applying the liner for better results, e.g., injection molded PFA liner with mechanical retainer as in ADMAG of Yokogawa. Normally manufacturers specify liner materials along with compatible flange material.

2. **Flow tube materials:** Normally stainless steel, alumina ceramics (99.9%);
3. **Flanges:** Carbon steel/stainless steel;
4. **Electrode material:** 316 stainless steel, platinum/rhodium, Hastelloy C276, Monel, titanium, and tantalum;
5. **Transmitter housing material:** Glass-loaded polypropylene, polycarbonate window.

Electromagnetic flow meter specifications are now discussed.

5.4.0 Specifications of Electromagnetic Flow Meters

The specification for an electromagnetic flow meter have been detailed in Table V/5.4.0-1. Data given here are best results from reputed manufacturers so may not match any particular model. Designer needs to frame the specification which best suits the application considering the given table as guideline.

TABLE V/5.4.0-1 Specification of Electromagnetic Meter (*Inline Type Mainly*)

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Clear liquid/liquid with solids		
2	Design pressure	Typically PN 10/16 but PN 25/40 also possible		
3	Design temperature	Up to 160°C even with remote transmitter		
4	Derating	Subsection 5.1.3.1		
5	Conductivity	Normally 5–20 µs/cm but with capacitive measurement possible as low as 0.05 µS/cm		
6	Environmental condition	Refer to Subsection 5.1.3.5		
7	Measurement type	Galvanic, capacitive type		
8	Output	Pulse/4–20 mADC Smart version with HART protocol, fieldbus communication (e.g., PROFIBUS/Foundation fieldbus) available.		
9	Output function	Electronic totalizer, remote transmission and other control function including filling control, etc.		
10	Materials of construction	Refer to Section 5.3.7		
11	Enclosure class	NEMA 4X/IP 66/67 IP68 is also possible		
12	Electronics unit	ABS, epoxy encapsulated		
Connection and Mounting Details				
13	Process connection & meter type	Flange ANSI/BS/DIN/JIS, etc. standard pressure rating matching application, e.g., PN 40/ANSI 300 class as standard. Screwed connection possible.		
		Meters are available in WAFER version also for mounting between two pipe flanges		

Continued

TABLE V/5.4.0-1 Specification of Electromagnetic Meter (*Inline Type Mainly*)—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
14	Electrical	½″NPT/ET ISO M20 or manufacturer standard		
15	Mounting	Horizontal/vertical/inclined		
Performance and Other General Details				
16	K factor	Refer to Subsection 5.1.4.1		
17	Accuracy	~02% AR; refer to Section 5.1.4		
18	Repeatability	0.1%		
19	Certification	Necessary certification from appropriate authority for hazardous application		
20	Application	Liquid services only but could be used for almost all types of fluid be it corrosive/abrasive, only requirement minimum electrical conductivity to be maintained		
21	Accessories	Grounding/protection ring, rate flow and totalizing indicator, transmitter, communication facility		
22	Hazardous application	Suitable certification from a competent authorities for transmitter also		
Transmitter Specification				
23	Type	Remote/integral		
24	Accuracy	0.25% AR		
24	Response time	<1 s		
25	Repeatability	0.15% AR		
26	Power supply	230 VAC 50 Hz or 110 V 60 Hz with suitable adapter and converter		
27	Feature	Forward and reverse flow monitoring, self-diagnostics.		
28	Communication	Support fieldbus communication. HART communication		
29	Special feature	If any to specify requirement		

5.5.0 Installation Discussions

Installation considerations mainly consist of physical end connection of the meter with a pipe, orientation of the flow tube and transmitter, etc. These activities also involve adjacent piping arrangements, accessibility, electrical connections, and good grounding practices (already covered in Section 5.3.0). In this section brief discussion will be presented on meter types, orientation, mounting, and associated installation requirements and considerations. Various installation arrangements have been depicted in Fig. V/5.5.0-1. In these arrangements, a flow meter without a transmitter, i.e., remote transmitter arrangements, has been depicted. However one should note that the same arrangement is equally valid for flow meters with integral transmitters. In these arrangements, wafer and flanged meters have been depicted. These would be the same screwed type connections (though they are not very popular).

1. **Meter types:** Electromagnetic flow meters are available mostly as flanged connections.

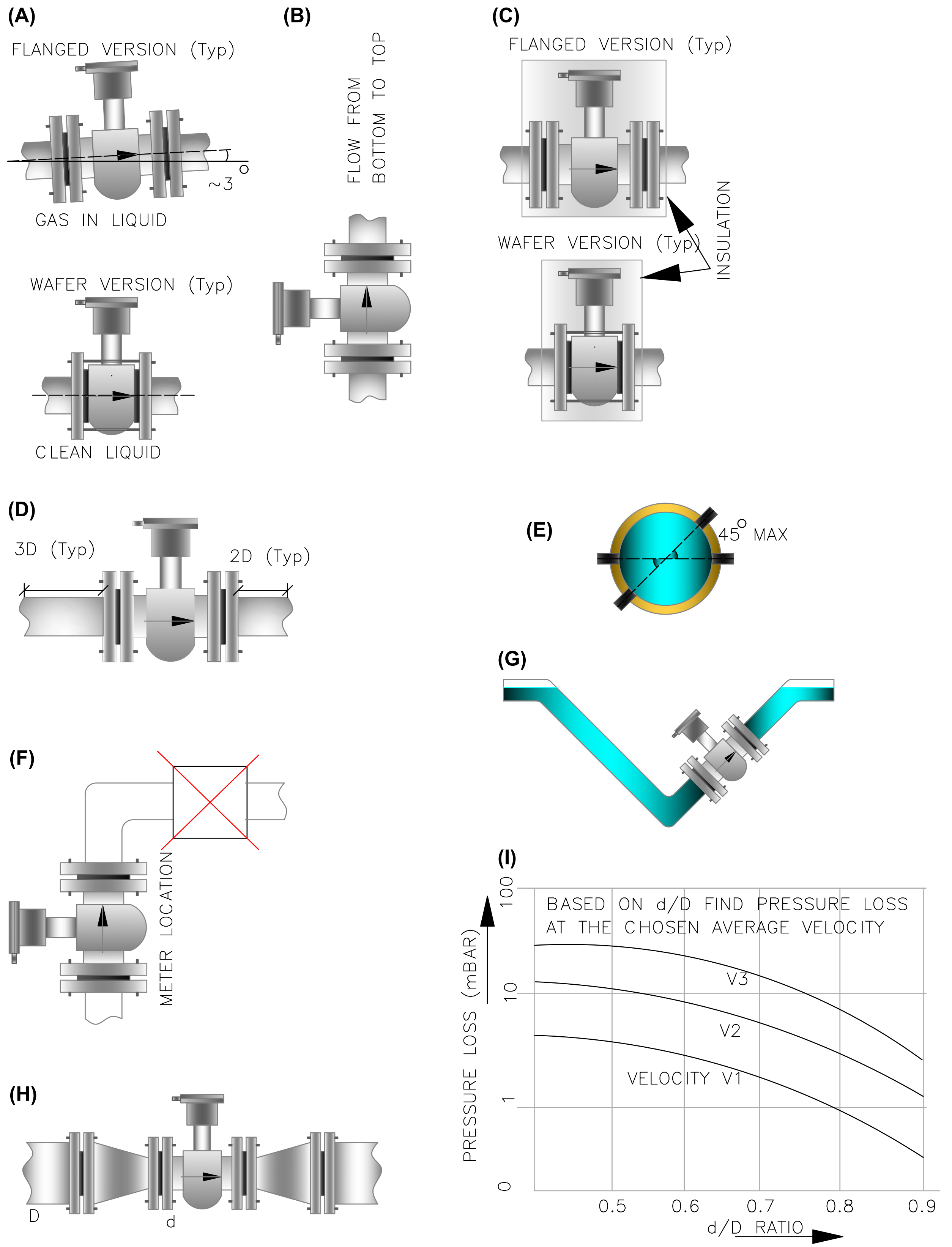


FIGURE V/5.5.0-1 Installation considerations for EMFM. (A) Horizontal. (B) Vertical. (C) For high temperature. (D) Typical straight sections. (E) Electrode axis. Electrode axis horizontal desired if not possible maximum 45 degrees as shown. (F) No meter at highest point. (G) Meter in partially filled pipe, (H) EMFM with reducer, (I) pressure loss nomograph. (1) Two versions, e.g., wafer and flanged, shown typically in two cases. (2) Meters with remote transmitter considered here but same is equally applicable for integral transmitter 3D (typ) 2D (typ) in all figures. *(A) and (E) Courtesy: ABB.*

Wafer versions of flow meters are also available for mounting between the two pipe flanges. Wafer type meters have been depicted in Fig. V/5.5.0-1A and C. Normally meters are factory set as for forward flow but can measure bidirectional flow.

2. **Orientation:** There is absolutely no restriction on the mounting position of the flow meter in horizontal or vertical to affect measurement accuracy as long as the meter is full with liquid and free from any entrained gas.
   - *Full pipe:* Why this restriction of full flow tube? When one recalls Eq. (V/5.0.1-3) or Eq. (V/5.0.1-4), one can see that flow measurement accounts for the full constant pipe diameter (D). Therefore, the equation will become invalid if the pipe is not full. Naturally if the pipe is not full or some entrapped gas displaces some liquid to be measured, there will be inaccuracy in the measurement (especially when gas is entrapped, because it may cause variable D). Similarly when there is build up in the meter wall this will reduce the diameter and hence it will affect the measurement accuracy.
   - *Electrode cleaning:* In the case of build up in the electrode (coating), it will also affect measurement. This is stated here because in the case of mounting suitable care should be taken to facilitate cleaning arrangements. Such coatings may be either conductive or insulating. Conductive coatings cause inaccurate outputs, while insulating coatings can prevent electrode contact with the process, creating erratic and unpredictable outputs.
3. **Electrode axis:** The electrode axis should always be horizontal or at best at an angle 45 degrees from the horizontal [35]. This is shown in Fig. V/5.5.0-1E. A vertical plane would expose the upper electrode to any air or gas at the top of the tube, affecting accuracy [31].
4. **Horizontal mounting:** Typical horizontal mounting of the meter in a pipeline has been illustrated in Fig. V/5.5.0-1A. In the case of liquid free from any entrapped gas referred to here as clean liquid, horizontal mounting as shown is well suited. However, if there is a chance of entrapped gas then it is better to have the meter axis at 3 degrees with the horizontal as shown. Such an arrangement will act as degasser [35] (Courtesy: ABB Limited).
5. **Vertical mounting:** Vertical mounting of the meter has been shown in Fig. V/5.5.0-1B. Here the designer has to ensure that the meter is full and measurement is free from entrapped gas, therefore flow in the vertical mounting should be from bottom to top. This arrangement is helpful in slurry applications because under no flow conditions solids will settle below the tube.
6. **Meter location:** The meter location is an important issue, especially to ensure the meter is full with liquid.
   - *Highest position:* The meter should not be positioned in the top-most/highest position, as in such an arrangement entrapped gas cannot escape and this affects measurement accuracy as already discussed. A typical arrangement for such a situation has been depicted in Fig. V/5.5.0-1F
   - *Partially full pipe:* If it is impossible to ensure that the meter tube is completely filled, then the arrangement shown in Fig. V/5.5.0-1G should be followed to ensure a full pipe. Also, a U arrangement (similar to siphon arrangement) can also be done for meter mounting.
7. **High-temperature measurement:** In case of high-temperature measurement the system should be insulated as shown in Fig. V/5.5.0-1C for both wafer as well as flanged versions of the meter. A remote transmitter is preferred if for high-temperature application.
8. **Straight section:** An electromagnetic flow meter does not require a long straight section either upstream or downstream. However, if there is some restriction like a bend, valve, etc. it is necessary to have a straight section

that is maintained in the inlet and outlet pipe sections as shown in Fig. V/5.5.0-1D.

9. **Flow meter with reducer:** It is not uncommon that, to meet the desired velocity, a lower size than the process pipe has to be selected. In such a case as is shown in Fig. V/5.5.0-1H a suitable reducer expander would be necessary. However for reducer arrangement there will be some pressure loss.
10. **Pressure loss in the reducer:** Normally the pressure loss in a line size meter is practically zero. However, as stated above there will be some pressure loss due to reducer arrangement. Also, such pressure loss will be a function of the d/D ratio and liquid velocity. Such pressure loss will be in the range of a few hundreds of mBar. For calculation of pressure loss, due to the reducer one can use a pressure loss nomograph from the manufacturer or necessary data supplied by the manufacturer. A typical pressure nomograph has been depicted in Fig. V/5.5.0-1I. If “d” is the reduced internal diameter and “D” is the internal diameter of the pipe, then the d/D ratio is calculated. The manufacturer’s supplied pressure nomograph shows the pressure loss versus d/D ratio at different liquid velocities. For the d/D ratio calculated pressure loss is found from the nomograph for the final desired liquid velocity.

5.6.0 General Start Up Procedure and Operation

From the discussions in Subsection 5.3.5.8 it is clear that in the case of a modern transmitter prior to putting the meter into operation it is necessary to carry out a few start up steps as listed below.

1. **Start-up steps:** Start up steps and precautions for individual meter numbers from different manufacturers may be different. Naturally, start up steps given by the manufacturer need to be followed. Here only the basic outline steps have been listed.
   - *Preliminary checklist:* After installation of a metering unit and converter, follow the instructions from the manufacturer, the preliminary checklist provided by the manufacturer should be followed to ensure that installation issues like flow direction, grounding, etc. are correctly followed. This is important, to avoid the risk of damaging the meter, e.g., if the power supply specified is not followed the meter may be damaged.
   - *Meter turning ON:* After preliminary checks are over, the meter is turned on and necessary parameters must be entered for proper system operation.
   - *Zero check and memory setting:* After basic system-related parameters are entered, zero checking is done followed by setting up of the memory which will carry out the program. After this the data entry and meter configuration are done.
2. **Operation:** Under operation basically the configuration data, parameter data, and range set value entries are carried out. These are followed by entering the menu sequence, which makes the system operate as per the program. This brief discussion has been presented for the reader to get an idea of the various steps necessary to make the meter operative. The actual procedure is more elaborative and dependent on the manufacturer’s instruction for the metering system and varies greatly.

Most meters are available with three-point calibrations for better accuracy. So far, discussions were on inline electromagnetic flow meter. Electromagnetic flow meters are also available in insertion types, and these are quite popular. Discussions on electromagnetic flow meters are not complete without discussions on the insertion version of the electromagnetic flow meter.

5.7.0 Insertion Type Electromagnetic Flow Meters

The major reasons behind its popularity are because of is lower cost for large pipe applications, i.e., it is unaffected by pipe size. Also, insertion type electromagnetic type flow meters are available in retractable versions and allow easier installation for wet-tap installations. Also, these

meters are available in battery-operated versions for remote location applications. In this section brief discussions on insertion type EMFMs shall be covered to complete the discussions on electromagnetic flow meters.

1. **Working method:** The discussions on insertion electromagnetic flow meters start with Fig. V/5.7.0-1. Basic principle of measurement is same, here only representative average velocity is measured to get the representative

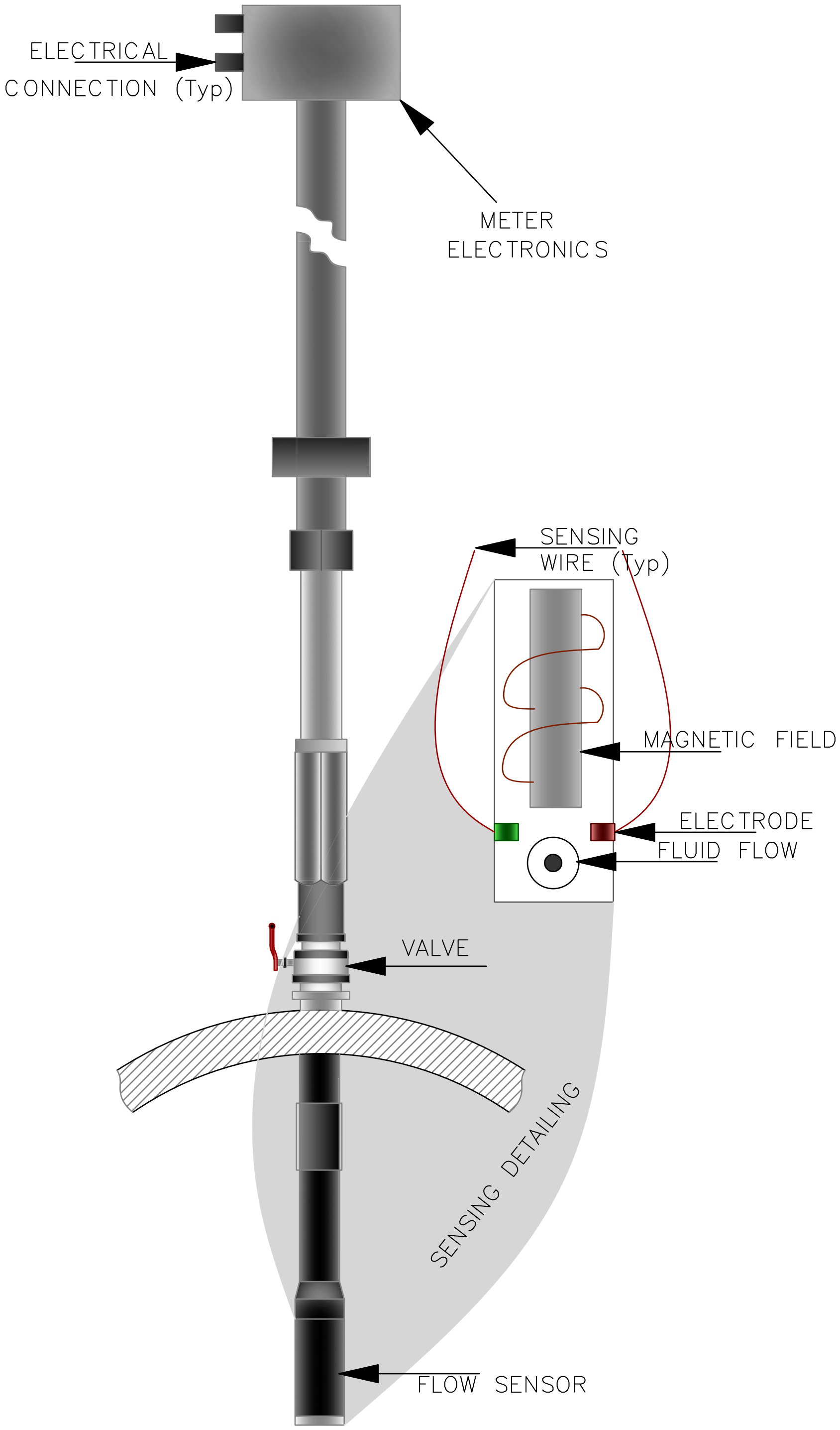


FIGURE V/5.7.0-1 Insertion type EMFM.

flow in the pipe from the diameter of the pipe. As shown in the blown-up view of the sensor in Fig. V/5.7.0-1, when the process liquid passes through the magnetic field generated by the excitation coil residing inside the probe, a voltage is detected by the electrodes that are embedded in the probe. The performance is highly dependent on the proper location of the sensor inside the meter. This insertion meter detects the flow velocity in only a small segment of the cross-sectional area of the larger pipe.

So, if the flowing velocity at that location of the insertion EMFM is not representative of the average velocity of the pipe cross-section, then there will be a substantial error in measurement.

2. **Features of insertion type meter:** The following are the major features of this type of the meter:
   - Suitable for permanent or temporary installation;
   - "Hot tap"/"wet tap" capability installation without flow interruption;
   - Installation in existing pipelines by tapping with a valve;
   - Possible for retraction for maintenance;
   - Possible to measure bidirectional flow;
   - Good accuracy possible over wide operating flow range;
   - Smart meters can support HART protocol, and fieldbus system;
   - Some meters are available in dual power, i.e., mains supply and battery backup.
3. **Specification of insertion type EMFM:** A brief specification of the insertion type EMFM has been given in Table V/5.7.0-1. Here it is important to note that depending on applicability, the basic specification of an electromagnetic flow meter (Table V/5.4.0-1) is also valid for an insertion type meter. Table V/5.7.0-1 includes specific data applicable for insertion type EMFMs.

TABLE V/5.7.0-1 Specification of Insertion EMFM (*Specific Data for the Meter Only*)—to be Read in Conjunction With Table V/5.4.0-1

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Clear liquid/liquid with solids		
2	Design pressure	Around 20 bar		
3	Design temperature	0–70°C		
4	Insertion length	Available from 250 to 1200 mm in different specific sizes—depends on manufacturer		
5	Pipe sizes	200–8000 mmNB		
6	Accuracy	±2% AR depending on velocity		
7	Max. flow	Depends on velocity and insertion length		
8	Repeatability	±0.5% AR		
9	Conductivity	>20 μs/cm		
10	Process connection	Screwed connection of suitable size in NPT/BSP		
11	Mounting	Vertical from top of pipe		
12	Application	Full pipe and partial filled pipe, but proper positioning important.		
13	Transmitter	Integral/remote transmitter		
14	Special feature	Battery-operated meters also available		

Maximum flow capacity, which is a function of velocity and insertion length, may be obtained from the manufacturer's data.

The discussion on electromagnetic flow meters is now concluded, and we now move on to the ultrasonic flow meter—another *velocity-sensing noninvasive nonintrusive electrical flow meter*.

6.0.0 ULTRASONIC FLOW METERS (USFMs)

Acoustic waves (>20 kHz) are used in ultrasonic flow meters (USFMs), which are a nonintrusive and/or noninvasive (ref: Fig. V/5.7.0-2) *velocity-sensing electrical transducer* for detection of flow in a pipeline. Ultrasonic flow meters were first introduced in Japan, in 1963 [9].

1. **Speed of sound:** The speed of sound in various materials is a characteristic feature of the material. The typical speed of US waves in some selected materials has been enumerated in Table V/6.0.0-1 to get an idea of how they vary with the state of matters.
2. **Measurement of the speed of sound:** The velocity of sound is a characteristic property of a fluid. When this is measured in conjunction with operating pressures and temperature, the result can be utilized for computing the density, concentration, etc. of the fluid. Similarly the deviation of speed of sound from its value at the operating condition of the fluid can be used to interpret contamination of fluid, or for detection of entrapped gas in the fluid, such as air entrapped in pulp slurry. Exactly in the similar manner it could be utilized to determine the volumetric fraction of the two components in a two-phase fluid, e.g., oil:water ratio in multiphase flow measurement. Therefore, the combination of volumetric flow and measurement of speed of sound together could be a very good tool in flow measurement, especially in multiphase flow measurement or for detection of any gas leakage, and contamination detection. The speed of sound measurement technique is also utilized in a separate measurement flow-measuring technique discussed in Section 9.0.0 in this chapter—SONAR which is also a good measuring technique in various applications.
3. **Ultrasonic flow measurement types and comparison:** There are two types of flow meters based on ultrasonic technology. These

Invasive & Noninvasive: *The transducers/sensors which come in contact with fluid (i.e. wetted) are invasive transducer/sensor. On the other hand if they do not come in contact with flowing fluid they are noninvasive type viz. ultrasonic flow measurement is noninvasive flow measuring system.*

Intrusive & nonintrusive: *When the flow sensor/transducer or meter is protruded into flow lines or changes the flow profile it is intrusive sensor. When the sensor does not change the profile it is nonintrusive. Inline Electromagnetic flow meter with galvanic sensing is (practically) nonintrusive but invasive. While same in case of capacitive sensing is nonintrusive and noninvasive similarly ultrasonic flow transducers are nonintrusive and noninvasive.*

FIGURE V/5.7.0-2 Invasive and intrusive flow sensing.

TABLE V/6.0.0-1 Speed of Sound Through Selected Materials (Velocity in *Meter/Second*)

Materials	Speed	Materials	Speed	Materials	Speed
Air	330	water	1480	Steel	3200–5900
Chlorine	210	Methanol	1100	Aluminum	3100–6400
CO_2/CO	280/336	Kerosene	1320	Copper	4600
Hydrogen	1280	Glycerin	1900	Wood	3960

TABLE V/6.0.0-2 Comparison of Doppler Type and Transit Time USFM

Point of Comparison	Doppler Type	Transit Time Type
Wave type	Acoustic wave with frequency >20 kHz	
Major device	Piezoelectric crystal is a key device of measurement	
Operating frequency range	650 kHz to 1 MHz	>1 MHz (1–5 MHz)
Transducer	Single unit transreceiver	At least a pair of transmitter and receiver
Fluid type	Liquids with solids dirt like in waste water. However they find wide range of application	Clean liquid less bubbles/solids. This is also used in gaseous application
Measurement parameter	Change in frequency ($v = K\Delta f$)	Change in transit time ($v = K\Delta T$)
Cost	Costlier compared to transit time type	Less costly
Partially filled	Possible measurement if transducers are below liquid line but at the cost of accuracy	Not possible
Accuracy	Good accuracy	More accurate than Doppler

f, frequency; *K*, constant; *T*, transit time; *v*, fluid velocity; Δ, change in.

are the Doppler type and transit time. Both have a number of similarities as well as a number of dissimilarities. It is better to compare the two types as given in Table V/6.0.0-2 to understand both systems well at a later stage.

There are two main, popular types of USFM, i.e., Doppler type and transit time USFMs. There is another kind called the correlation type which has been explained in Chapter I and is not repeated here. Also, this type of meter is not very popular. In spite of several similarities between them, in operation they are not same. In this section brief discussions on their basic theory of operation shall be discussed. In this connection Subsection 1.2.2.10 and Fig. I/1.2.2-7 may be referenced.

6.0.1 BASIC THEORY OF OPERATION OF DOPPLER TYPE USFMs

In 1842, the Austrian physicist Christian Johann Doppler (1803–53) first observed and predicted that as long as both source and receiver are

stationary with respect to the propagating medium, the receiver will receive the same acoustic wave with the same frequency. On the other hand, whenever there is relative motion of either source or receiver with respect to the propagating medium, the frequency of sound received by the receiver will be a function relative to the motion of the source or receiver with respect to the propagating medium. Street traffic radars operate on this principle. When a person is standing near a factory horn this person will receive the same signal from the factory siren. Now, when this person moves away from the factory, the frequency of the siren will be lower pitched and when the person is moving towards the factory the frequency of siren it will be higher pitched. When the distance between the source and observer (receiver) increases, the sound wave needs to travel a longer distance to reach the observer. The speed of sound in the medium is fixed. Therefore, it will take more time to travel, i.e., the wavelength will be longer and thus the frequency will be shifted. This phenomenon has been depicted in Fig. V/6.0.1-1A. In fluid flow measurement, as indicated in Subsection 3.1.3.4 of Chapter I, there would be one set of transducers comprising one transmitter and one receiver as shown in Fig. V/6.0.1-1B. It is also possible that there would be single device containing both a transmitter and receiver as shown in Fig. I/3.1.3-4A. Flow measurement by Doppler effect requires that there be a small amount of gas/entrapped solid, i.e., sonically reflective material. Normally the transmitter and receiver are placed on the same side of the pipe as shown in Fig. I/3.1.3-4. The transmitter emits ultrasound of a known frequency (in the range of 1−5 MHz). In the presence of sonically reflective gas bubbles or entrapped solid particles which are moving at the same velocity as the fluid (due to flow) they will reflect the sound wave. Thus when the receiver receives the signal there will be a frequency shift. Mathematical expression of the same with the help of Snell's law has been shown with the help of Eqs. (I/3.1.3-1)−(I/3.1.3-3). Now this will be elaborated on a little differently.

As stated earlier, US waves strike sonically reflective materials moving at velocity v. Now the wavelength of the emitted wave at frequency Ft will be: $\lambda = C/Ft$, where $C =$ velocity of sound. Since transducers are outside the pipe, Snell's law can be used. Manufacturers use the same materials for both the transmitter and receiver, so instead of separate angles the same angle (θ) can be chosen.

Now the wavelength of transmitting wave will be

$$\lambda t = (C - v \cdot \cos\theta)/Ft. \qquad (V/6.0.1\text{-}1)$$

Thus the reflective wave will be

$$\lambda r = (C - 2 \cdot v \cdot \cos\theta)/Ft. \qquad (V/6.0.1\text{-}2)$$

or

$Fr = C \cdot Ft/(C - 2 \cdot v \cdot \cos\theta)$, ignoring $2v\cos\theta$ with respect to C. Therefore,

$$\Delta F = Fr - Ft = (2vFt\cos\theta)/C \qquad (V/6.0.1\text{-}3)$$

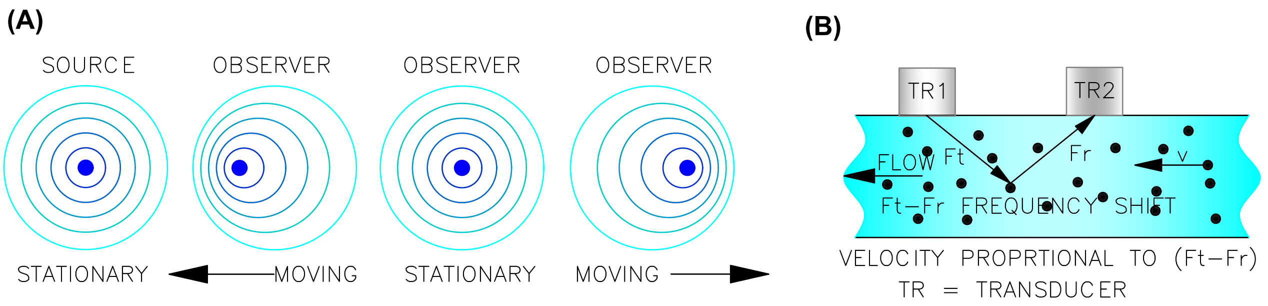


FIGURE V/6.0.1-1 Doppler type USFM theory. (A) Sound wave and Doppler effect. (B) Doppler effect in USFM.

or

$$v = C\cdot\Delta F/2Ft\cos\theta;$$

or

$$v = k\cdot\Delta F$$

because Ft is a known constant, C is constant for the medium, Cosθ is also a known constant. Now for a known pipe area, flow can be obtained from

$$q = AV = \left(\pi D^2/4\right)\times k\cdot\Delta F \text{ or } q = K\cdot\Delta F \quad (V/6.0.1\text{-}4)$$

where K is the meter factor. When this deduction is compared with that in Chapter I it can be seen that both are the same, with two methods of arriving at the same result. *Water flow at 1 m/s and 60* degrees *angle of strike would give a Doppler shift of around 640 Hz* [5].

6.0.2 BASIC THEORY OF OPERATION FOR TRANSIT TIME TYPE USFMs

In transit time type USFM, principle, the difference of transit time of ultrasound to travel a definite distance with and against flowing fluid is computed to get the velocity of fluid. When a sound wave travels across the pipe filled up with fluid the time taken depends on the speed of sound in the medium. However, this is not the case when the medium is flowing inside the pipe. The time taken by an ultrasonic wave to travel across a pipeline depends on the velocity of the ultrasound as well as the velocity of the flowing medium. Here the direction of flow is important, as in one direction the transit time is reduced (while traveling with fluid flow), while in the opposite direction the transit time is increased. In actual transit time measurement two types of USFM are used. In the direct type, an ultrasound pulse traverses across the pipe. In the other type ultrasound has to take two traverses, i.e., an emitted pulse has to traverse across the pipe and get reflected at the pipe surface then traverse as a reflected wave. So, in the direct method transducers will be on two opposite sides of the pipe. In the reflective type both transducers are placed on the same side of the pipe. Both cases are depicted in Fig. I/3.1.3-4B. The mathematical deductions are given in sets of equations: Eq. I/3.1.3-4 through Eq. I/3.1.3-9 and are sufficiently detailed so are not repeated again here.

6.1.0 Descriptive Details of Ultrasonic Flow Meters

As it has a noninvasive and nonintrusive nature it can be used to measure corrosive fluids. However, flow measurement by ultrasonic flow meters is affected by a number of factors such as flow profile, pipe influence, environmental interference, as well as temperature of the flowing fluid, etc. So, after gaining some knowledge on the theory of operation it is important to know about the total description of the system and its construction and mounting arrangements. USFM normally consists of a set of transducer(s), electronics housing, pipe section, and/or spool piece. Here the pipe section is described to indicate clamp type connections. Calibration is an important factor and it is necessary that the customer provide all necessary data to the manufacturers so that they can suggest the meter and calibrate the meter. For US meters all process data, flow profile, and piping data are of utmost importance.

6.1.1 DESCRIPTIVE DETAILS OF DOPPLER USFMs

The basic principle of operation and associated theory have been discussed at length. From there two major issues arise:

1. Liquid should contain sonic reflective materials such as oil, gas bubbles, and/or suspended solids.
2. On account of the Doppler effect, there will be a Doppler shift frequency (Δf), which is directly proportional to the velocity and hence the flow rate.

So far as mounting of Doppler type flow meters are concerned, these are available in various versions. These include a spool piece version, in which pipes have a short piece welded in to which transducers can be placed through a flange connection or screwed. The other method could

be that the transducers are externally clamped with the main pipe. In the case of a Doppler type USFM, a single-transducer system is more popular than two separate transducers. In this design both the transmitter section and receiver section, each with piezoelectric crystals, are packaged in a single unit or transducer assembly to be mounted on the outside of the pipe. Both a single transducer and two transducers (both sides and on the same side) are shown in Fig. V/6.1.0-1.

Fig. V/6.1.0-1A shows the single transducer in a spool piece. This is not noninvasive. The other two shown in Fig. V/6.1.0-1B are the two-transducer design where both the transducers are clamped with the pipe and noninvasive. Here the alignment and fixing are important, so typical alignment and fixing hardware have been depicted. Here the transducers could be on the same side of the pipe or be at opposite sides as also shown. The manufacturer properly maintains the alignment of crystals of transmitter and receiver. Misalignment could result in an error in the system. If there is a large quantity of entrapped/suspended solids, then the velocity of them near the measuring well will be less than the average velocity, and due to the tendency for their accumulation near the well there could be error in reading in the single transducer option. For this, the two-transducer approach (supplemented by range gating) could be better [9]. In the case of multiphase flows, the particle velocity may not bear a proper relationship with the media velocity, so use of this technology in multiphase flow measurement may not yield good results. Also as stated earlier, even in liquid flow measurement the velocity of the particles is dependent on the position of the particle, so there may be several different frequency shifts [5]. Therefore it is extremely important to ensure that the reflected ultrasonic radiation is received from a more representative portion of the liquid. In this connection the manufacturer's instructions for mounting should be followed strictly. Another important issue here is that a particle is seen only when it is approximately 1/10th larger than the wavelength of the acoustic wave in the liquid. Therefore, assuming 1500 m/s is the speed of the US wave in water, then for a 2-MHz ultrasonic beam the wavelength will be 0.75 mm. Therefore, the minimum particle size should be larger than 0.075 mm or 75 μm for proper reflection to take place. In the case of bubbles, oil particles, and sand reflections would be much better. Discussions may be concluded with the view that Doppler USFM is a cost-effective solution for measurement requiring moderate accuracy.

6.1.2 DESCRIPTIVE DETAILS ON TRANSIT TIME USFMs

While the presence of foreign materials is necessary for working of Doppler type USFM, in transit time type USFM, the fluid should be clean,

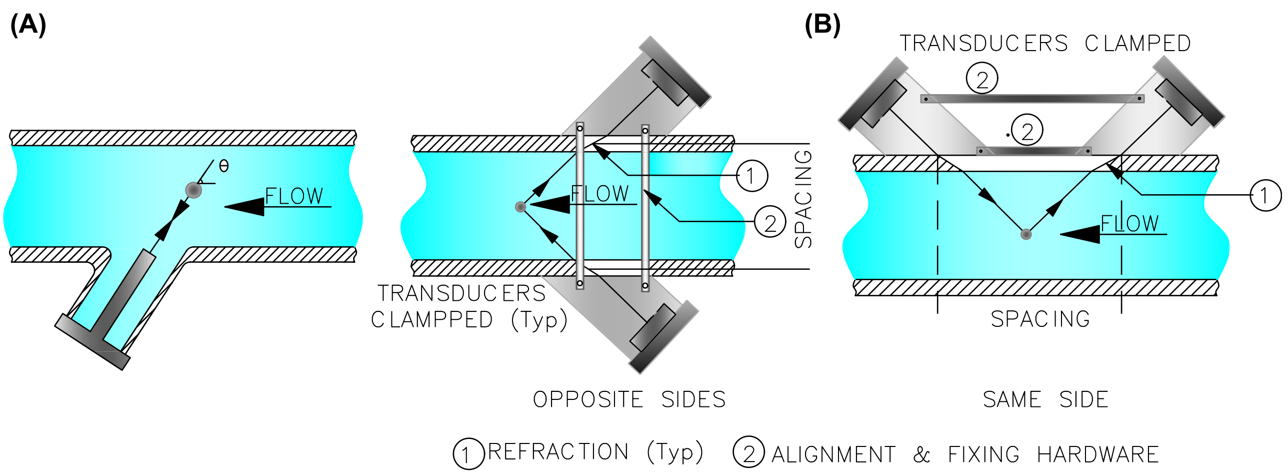


FIGURE V/6.1.0-1 Doppler transducer types. (A) single transducer Doppler. (B) two transducers Doppler.

such as water, air, natural gas, etc. In the case of USFM in *gas* applications there are a few requirements. As the sound waves need a medium to travel through, for transmission of sound between sensors the gas medium in between must be a defined minimum density, pressure, and temperature. These minimum parameters are defined for a particular meter and notified in advance. Also, the edges of components normally found with piping can generate US sounds. For this reason a straight run of inlet pipe section is an absolute necessity for gas flow applications.

There are several versions of this type of flow meter available, as shown in Fig. V/6.1.0-2.

As stated in connection with Doppler type, the transducer could be fit into a spool piece welded with the main pipe (top leftmost image in Fig. V/6.1.0-2A). The other option could be a flanged type. As stated earlier, there are two options in which transit time USFM can work. The first is direct and is shown in Fig. V/6.1.0-2A. In this method a set of transducers is placed in such as way that each one sees the other. In this method signals are sent and received by both transducers. Depending on the flow direction, one set of signals will be with the flow direction and the other will be against the flow direction, so it will be easier to calculate the transit time difference, as already discussed in Section 6.0.2 of this chapter. The other type is reflective, as shown in Fig. V/6.1.0-2B. In this method transit time is the measuring parameter, however measurement is not as easy as it appears to be. A few challenging issues are listed here.

- Accurate measurement of transit time;
- Elimination of signal inconsistency between upstream and downstream signal paths;
- Elimination of installation errors;
- Combating short circuiting of US waves.

We now look into the details of these methods. US waves in water move at a speed around 1500 m/s. In a 300-mm diameter pipe, for example, with the transducers set at 45 degrees, and the media flowing at 1 m/s, the transit time is about 284 μs and the time difference ΔT is less than 200 ns [5]. From these data it is clear that to get an accuracy of, e.g., 1%, the level at which

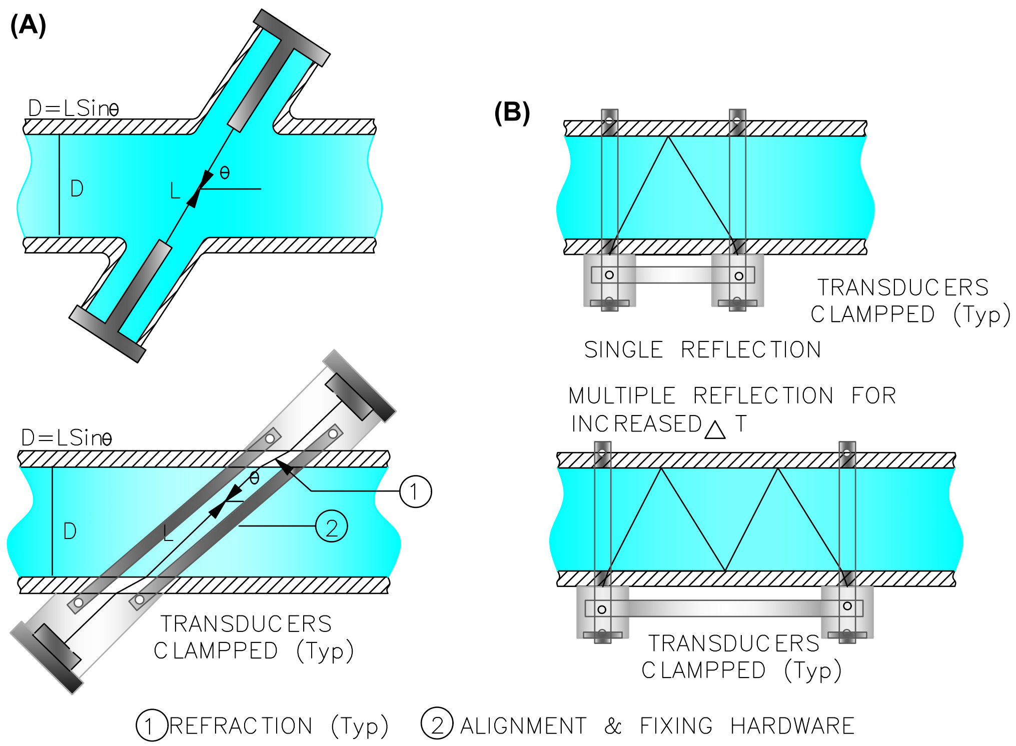


FIGURE V/6.1.0-2 Transit time transducer types. (A) Direct transit time. (B) Reflective transit time.

the measurement is to be carried is in the nano (10^{-9}) second range. For smaller pipes it could be a much lower range, maybe in pico (10^{-12}) seconds. Theoretically it may sound ok but in reality at times these are not very easy, especially for smaller pipes. *What is the solution?* The only possibility left is to increase the length of the path so that the transit time and hence the transit time difference ΔT increases. This can be done easily in reflective type with the help of the pipe surface to create several reflections of the US wave before it reaches the receiver. Also, it has been found that performance of this type of meter (reflective) is much better for larger pipes with several traverse paths (inline meters are not considered). Obviously in this method some energy will be lost. In addition, as the spool piece is an integral part of the hydraulic system, spool piece type of mounting cannot be used in the existing system without it stopping. Hence they cannot be used in retrofit projects. From easy installation and noninterference points of view clamped transducers are always preferred in ordinary meters. However a number of issues should be considered. As indicated in the case of the Doppler meter, alignment and fixing are also important here. Normally associated hardware and accessories are supplied with the main supplies. However, it is better that mounting/installation (i.e., drilling holes, welding of hardware) be done under the guidance of the manufacturer. Since the meters are fixed outside the pipe the US beam will undergo refraction at two stages when the beam crosses the pipe boundary from (and to) the medium. This has been shown in Fig. V/6.1.0-2. These are stated here because this is to be considered while aligning the transducers. Gas flow USFM and custody transfer USFM are inline USFM, and their operating principles are also transit type as discussed. Inline USFM has been discussed separately in Section 6.5.0 of this chapter. Now we investigate other types through brief discussions to complete the description of USFMs.

6.1.3 DESCRIPTION OF OTHER TYPES OF USFM

There a few other types of USFM. These are basically derived from transit time type. They are discussed in the following subsections to complete the discussions on USFMs.

1. **Sing around type:** There are two measuring paths as shown in Fig. V/6.1.0-3A. In this arrangement when a pulse is received at the receiver the next US pulse is sent. This is popularly known as a sing around type on account of its method of operation. The frequency of the transmitted pulse is proportional to the velocity of the flowing medium and inversely proportional to the distance traversed, which is fixed for a set of transducer in a pipe. The relationship of Δf with velocity is as given in Eq. (I/3.1.3-9), i.e., $v = \Delta f.\ L/2\cos\theta$ or, $\mathbf{v = K \cdot \Delta f}$.

   In this type of transducer mounting by a spool piece is preferred to clamped transducers. Both types have been depicted in Fig. V/6.1.0-3A. According to B.G. Liptak "Potential errors caused by 'ringing around the pipe' (pulse blockage by a molecular layer of air between the pipe and its lining, or variations in travel distance due to changes in the angle of refraction) are more difficult to solve with clamp-on units than with wetted ones" [9]. There is another type known as the phase shift type.
2. **Phase shift type:** This is basically a transit time type. The difference here is that, in this method there will be a separate external reflector used. The transducer external to the pipe transmits a US beam which crosses the pipe and then is reflected by the external reflector discussed above. After reflection it is received at the receiver. When US beam undergoes a phase shift in transit time that is proportional to the average velocity of the flowing fluid times the path over which the velocity is encountered. The receiving transducer

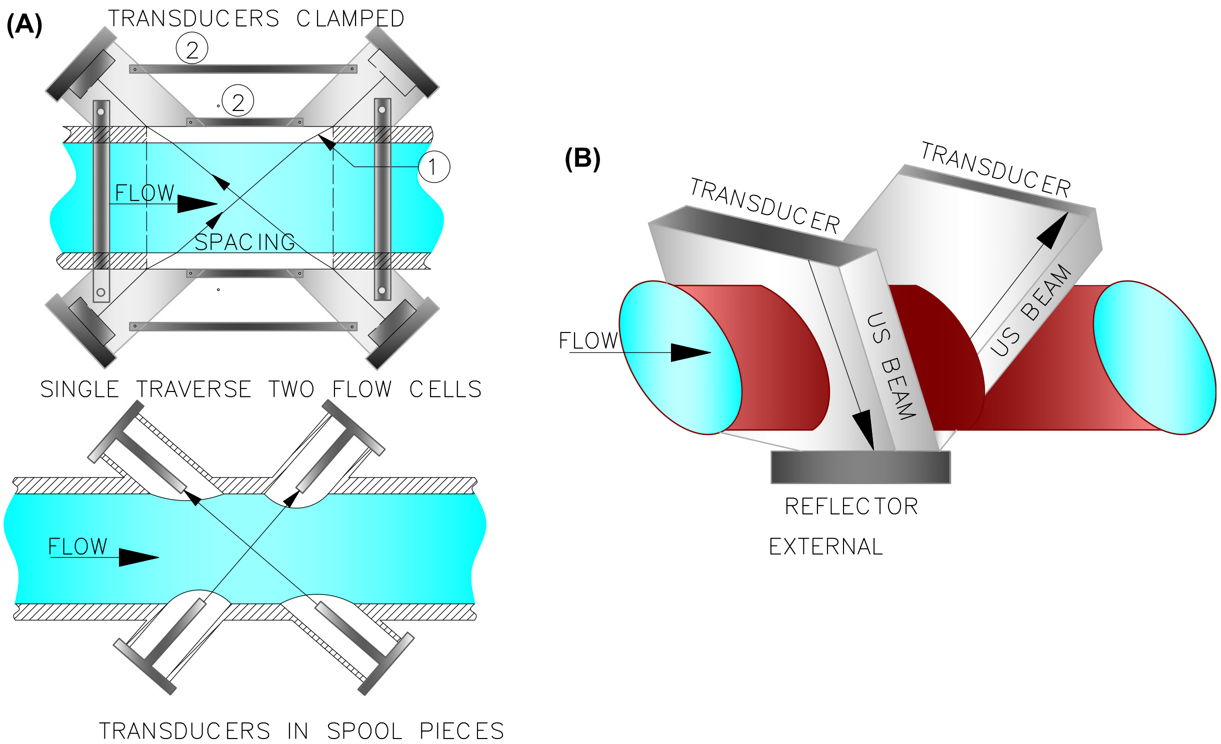


FIGURE V/6.1.0-3 Other transducer types. (A) Sing around type. (B) Phase shift method.

is required to integrate this velocity length product over the entire width of the pipe to get the volume flow. Also, as the integration is done over the entire pipe width, the computed volume flow is independent of flow profile. Thus in this method a change in flow profile does not have any effect in flow calculation. This type of transducer and reflector has been depicted in Fig. V/6.1.0-3B. There is another kind known as drift, but these are rarely used in industrial applications.

6.1.4 TRANSDUCERS

Transducers and associated electronic hardware complete with associated software for flow computation and external communication are the major parts of ultrasonic flow measurement. Of these, the transducer is at the heart of measurement. The transducer contains a piezoelectric crystal which produces mechanical energy in the form of vibration, i.e., ultrasound when current is applied. Whereas when it receives the mechanical force in the form of vibration, it produces electricity in the receiver. In this connection Fig. V/6.1.4-1 may be referenced.

Normally transducers are put in a small piping section known as a flow cell. Flow transducers are mounted inside the flow cell which is used to mount the transducers. From the discussions in the previous section USFM transducers can be categorized as listed below.

1. ***Wetted* transducer:** As the name suggests, wetted transducers come directly in contact with the fluid being measured and can be inserted through a spool piece. Generally wetted transducers send and receive longitudinal ultrasonic wave signals into the fluid. These are usually flat-faced and, as these are wetted types, the signals go to the fluid without the need for any refraction. Typical wetted transducers have been detailed in Fig. V/6.1.4-2A. There are several sizes of wetted transducer that manufacturers offer and these may range from around 1 cm to 30 cm in diameter.

Piezoelectricity & Piezoelectric Phenomenon: *From basic physics it is known that some crystalline ceramic materials (or with polymer film) show piezoelectric property. These materials are polarized with both positive and negative charges throughout two surfaces. So, when these materials are subject to mechanical force (as in pressure transducer) or mechanical vibration (as in case of ultrasonic receiver) they produce current. Similarly when current is passed through them they change their shape and size to produce vibration of desired frequency as it happens in ultrasonic transmitter. The electricity generated in this way is referred to as piezoelectricity. The entire phenomenon could be referred to piezoelectric phenomenon.*

FIGURE V/6.1.4-1 Piezoelectricity and piezoelectric phenomenon.

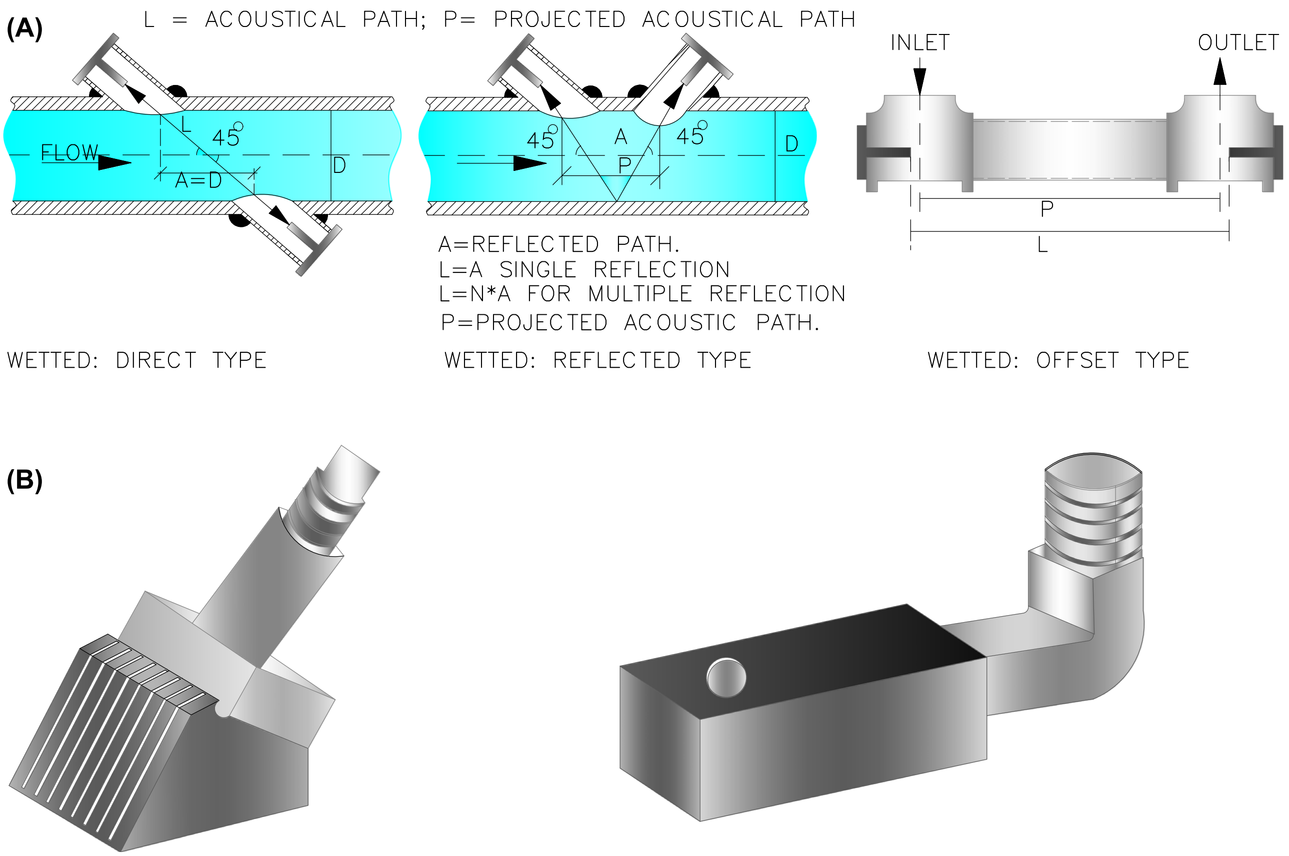


FIGURE V/6.1.4-2 USFM Transducer details. (A) Wetted type transducers. (B) Clamped type transducers. *This diagram has been developed based on an idea from Panametrics Ultrasonic Flow Transducers for Liquids, Installation Guide, 916–055B, GE Senesing, July 2007. https://www.gemeasurement.com/sites/gemc.dev/files/ultrasonic_transducer_iinstalation_guide_for_liquids_english.pdf. Courtesy: GE sensing.*

The two main types of connections are described here.

- *Tilted diameter:* This is the most common type shown in the first two figures of Fig. V/6.1.4-2A. These are used for both direct and reflective type measurements. The minimum diameter of the flow pipe should be 50 mmNB. As shown in this type, the incident beam from the transducer is tilted with respect to the pipe axis (45 degrees being typical). On account of this tilting incident beam this is called the tilted diameter. These are used for direct or reflective type meters and also for single or multiple traverse meters. The acoustic path is designated as L, while projected acoustic is represented by P, which is very important for spacing of transducers discussed in connection with clamped types also. For better understanding, each reflection path has been represented as A. So, for a single reflective part A = L. For multiple traverse based on the number of traverse paths (N), the acoustic path will be L = N.A.
- *Axial offset:* When the pipe diameter is small it is very difficult (especially for transit time) to work with a tilted diameter; in these cases, axial offsets as shown in Fig. V/6.1.4-2A (rightmost diagram) are used. These are available in very small sizes (e.g., 6 mm up to 50 mm). The flow cell can be developed with the help of a spool piece for connecting to the existing pipe or through cold type of tapping [36]. In this method, the walls of the pipe reflect the ultrasonic signal so that the signal remains in the fluid for longer to provide an increased effective length L. This enhances accuracy. The number of times the signal can traverse the fluid depends on such factors as transducer frequency, pipe size, pipe wall condition, and the fluid being measured [36]. Excellent accuracies are available in this type of transducer as it allows longer path through multiple reflections and almost 100% flow profile coverage.

2. **Nonwetted transducer (clamped-on transducer):** These are also known as clamped transducers as these are mounted outside the pipe (hence they are noninvasive). Since these are clamped outside the pipe, for sending and receiving signals to and from the fluid, ultrasonic waves will undergo refraction. These flat-faced transducers are available in suitable housing which could be directly clamped to the outside surface of the pipe. Clamped-on transducers are meant for using in pipes of sizes above 50 mmNB. The most common types of clamp-on transducers have a weatherproof casing [36]. Pipes can be made of various materials such as carbon steel, stainless steel, copper, brass, cast or ductile iron, glass, plastic, or fiberglass. As long as the wall can conduct sound adequately, there are no thickness constraints on the pipe wall [36]. Transducers for small pipes are also available in preinstalled manner.
3. **Positioning and location of transducers:** It is needless to say that the positioning and location of the transducers in USFMs is extremely important, not only for measurement accuracy but also for measurement to happen. Other associated points to be taken into consideration are spacing, alignment, and electronics functioning, and programming of secondary electronics. The following points also need due consideration:
   - *Location:* The flow cell should be located a minimum 10 D (pipe internal diameter) of straight length upstream and 5D of straight length downstream to get an undisturbed flow profile.
   - *Mounting:* Transducers should be located in a horizontal plane, especially in horizontal pipe installations. In horizontal pipes transducers cannot be mounted at the top or bottom. If the flow has some entrapped gas then it will tend to accumulate gas at the top and sensing will be wrong. Similarly, if the liquid contains sediment it will tend to accumulate at the bottom, hence the bottom transducer may become blocked and so this is an unsuitable location.

As long as the pipe is full there is no restriction for mounting of transducers in vertical pipes. Only flow downwards in vertical pipes should be avoided. Once the thickness of the pipe and temperature and fluid type are known this information can be inputted into the computing circuit to calculate the required spacing [37]. The preferred location and positions of transducers at various applications have been depicted in Fig. V/6.1.4-3. This is important for fixing transducers.

6.1.5 SECONDARY ELECTRONICS FOR USFMs

Unlike many other types of meter in case of US meter secondary electronics plays major role for measurement and its performance. From the discussions it is clear that there a number of ways in which the measurement can be carried out. Naturally, each will have some specific requirement of circuit configuration. However, one thing is for sure—each system will have a transducer(s). In the following generalized discussions and

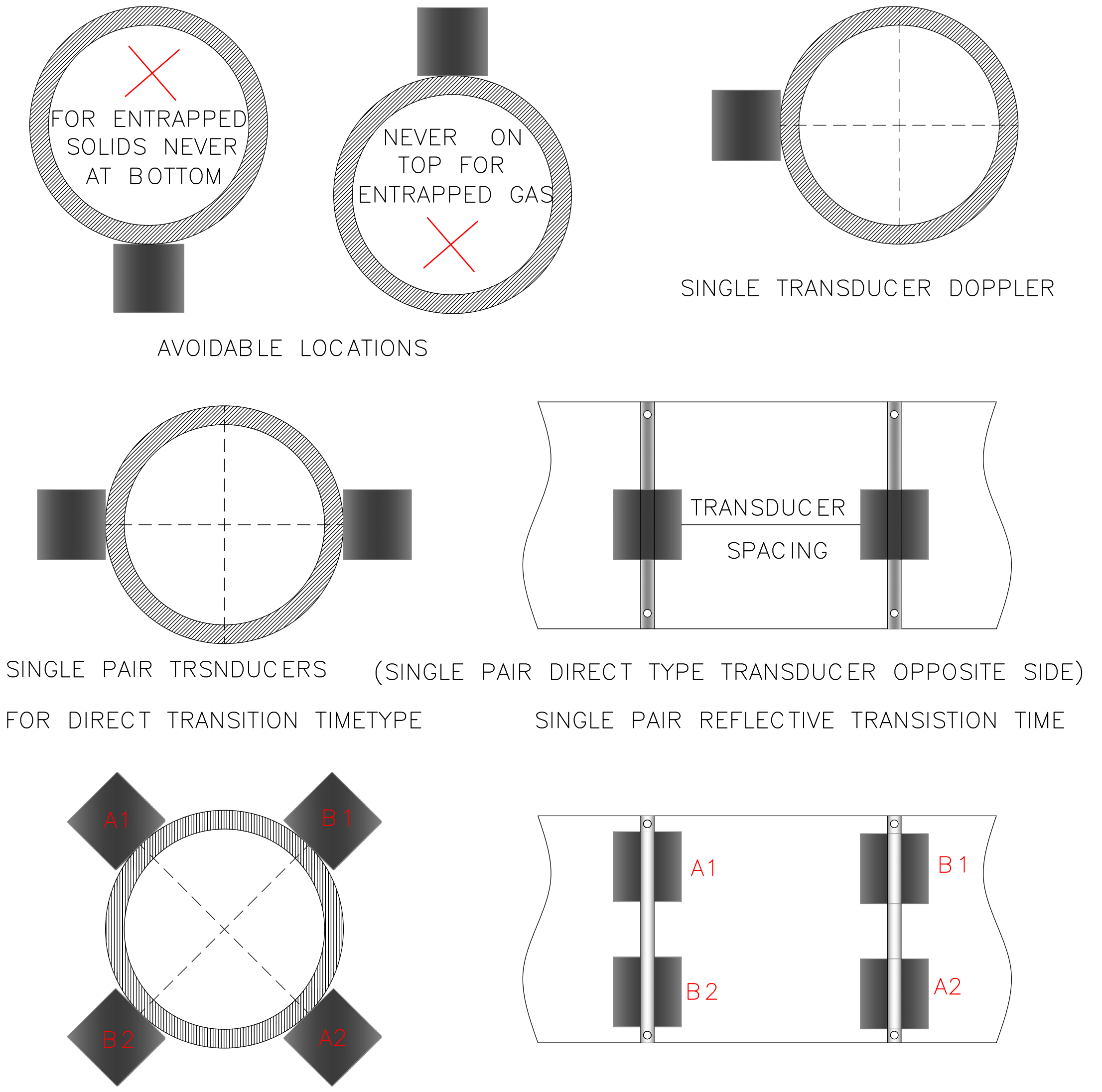


FIGURE V/6.1.4-3 Transducer positions and locations.

requirements are covered. For specific requirements the manufacturers' manual should be referred to.

1. **Signal processing unit:** As already discussed, a transducer consists of one transmitter section and another receiving section put in one flow cell. All US type measurement (even in Doppler type Transmitter and receiver in single packaging) measurements require at least a pair of transducers. Therefore, one pair has been considered for discussion. The discussion starts with reference to Fig. V/6.1.5-1.

There are two parts to a transducer: the transmitter used to generate a US pulse signal, and the receiver used to detect the US signal

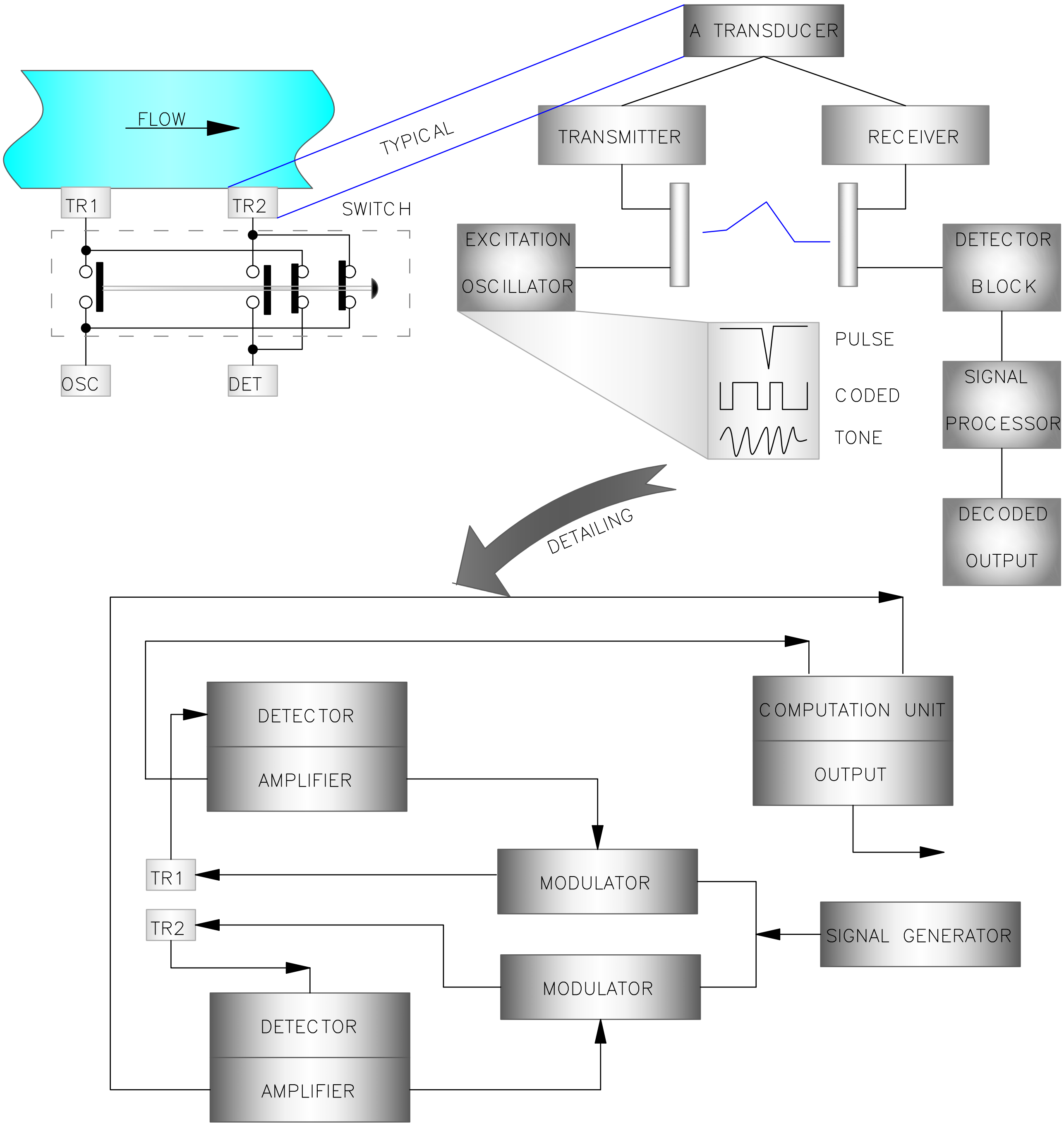


FIGURE V/6.1.5-1 USFM electronics.

sent through the flowing medium. Therefore, to generate a US signal some electrical excitation in the form of an oscillator is necessary. The oscillator has been shown, but for better results the signal from the oscillator is modified and modulated to generate the necessary US signal pulse at the desired frequency. The US signal could be a normal short-duration pulse or a tone pulse duly modulated and processed, or it could be a digitally processed coded signal as shown. This US signal pulse is detected by the detector which needs to first demodulate the signal to get the US signal. After the US signal is extracted, it is processed and sent to the computation section to get the desired digital/pulse output. If an analog 4–20 mADC signal is necessary then the signal undergoes further signal conversion. When a pair of transducers work in tandem, then, one transducer (e.g., TR1) transmits a signal to the other one (e.g., TR2), which receives it and the next transmitter (TR2) transmits the signal to be received by the other transmitter (TR1) to complete one measurement cycle. Thus it is clear that in order to carry out these transmissions and receptions alternately a switching circuit is necessary. In the figure the same switching has been shown by a simple switch/push button for understanding only. In reality there will be an electronic switch for this alternate action. A generalized block diagram of USFM electronics based on the above explanation has been presented at the lower part of the same figure. Also, the signal conversion and output formation are part of the signal processing unit.

2. **Diagnostic system:** Modern meters have intelligent self-diagnostics and diagnostic tools to detect and resolve meter problems.
3. **Operator interface:** USFMs normally have an operator interface connected with the remote electronics. The operator interface mainly consists of a display unit and operational keys. In the front panel there are a number of lines (depending on the manufacturer) of LED or backlit LCD displays. Normally these displays include rate flow, totalized flow, controlling information, and/or log book information. The system also controls a number of keys for parameter selection, reset, and other controlling functions.
4. **Transmission and communication:** One part of secondary electronics is to convert pulse and other forms of signals into analog output and/or digital output in the form of RS 232/485 (MODUS). Almost all meters are now smart meters that support HART protocol and fieldbus, so the communication interface is another part of the secondary electronics.

   With this, the discussions on descriptive details on USFMs (for inline USFMs refer to Section 6.5.0) comes to an end. We now see how USFM interfaces with process and stringency put on the meter from process.
5. **Mode selection:** There are two modes of selection normally found; these are the operational mode and programming or configuring mode. In the operational mode data and measure validity and check request are the operational requests. In configuration mode configuring the meter for the specific application is carried out. Normally meters are factory programmed.

6.2.0 Meter Performance and Associated Factors

There are a number of issues which influence the performance of USFMs. Of all of these factors the most obvious one is the Reynolds number effect. From the basic discussions of flow profile in Chapter I, it has been shown that this dimensionless number (Reynolds number, see Subsection 1.1.2.2 of Chapter I) actually gives the combined effect of density, viscosity, and pipe diameter on the flow, i.e., flow profile. Similarly there are a few other factors such as entrapped gas/solids, and installation issues also affect USFM flow meter performance. In this section short discussions shall be presented on those issues which influence USFM performance.

6.2.1 REYNOLDS NUMBER AND FLOW PROFILE EFFECT

1. **Recapitulation:** If one recalls the discussions in Chapter I, it has been shown that for Re <2000 flow is laminar and Re between 2000 and 4000 it is transition flow, while Re >4000 it is turbulent flow. So, when viscous forces are dominant it is laminar flow, whereas when inertial forces are dominant it is turbulent flow. Also it was seen that the velocity profiles in both cases are different. Laminar flow shows peak velocity at the center while with turbulent flow it is much flatter. In this connection, Fig. I/1.1.2-8 may be referenced.
2. **Explanation:** Ultrasonic flow measurement, in laminar flow conditions, with a single transducer, averages over the peak of the parabolic flow profile. In contrast, for turbulent flow it averages by way of the much flatter square profile. There is no need to explain that the measurement results will be different. What does it mean? It means that, for example, in a petrochemical/chemical plant there are, e.g., a number of fluids each with different viscosity passing through the same pipe—if the viscosities are widely varying there could be laminar and turbulent flow. Naturally, with single flow measurement transducers there will be an error in measurement.
3. **Remedial measure:** It is always the aim of measurement to make it independent of Reynolds number. This could be achieved by using ever greater numbers of transducer pairs, so that each will take a different measurement as in that case the actual flow profile is properly traced with the help of the number of transducers. This has been clearly shown in Fig. V/6.2.0-1.

There is another correction factor introduced to correct the measured velocity.

$$\text{Correction factor } K_h = \frac{\text{mean velocity}}{\text{Measured velocity}} = v_{mean}/v_{measured} \tag{V/6.2.1-1}$$

The values of K_h for laminar flow and turbulent flow are given by 0.76 and 0.94, respectively. The plot of K_h with velocity at various viscosity and pipe sizes is available for introducing the actual K_h value for computation.

6.2.2 INSTALLATION EFFECTS

The meter accuracy in an actual industrial set up after installation could be far from the claim by the manufacturer for that meter. These disturbances can come from the distortion of the flow profile on account of installation. When there are disturbances such as single or double elbows at different angles, reducer expander, etc., there will be a disturbance in the flow profile. When there are no disturbances and there is a fully developed

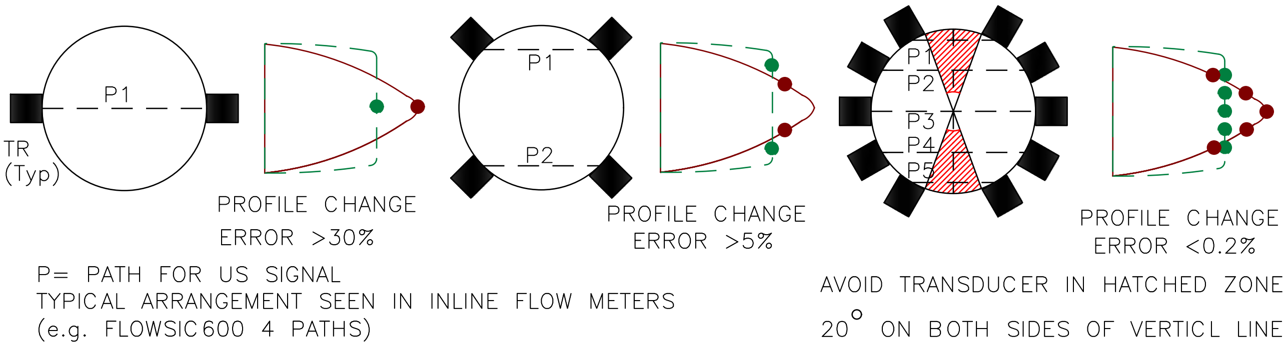


FIGURE V/6.2.0-1 Flow profile and meter performance. *Developed based on an idea from Fundamentals of Ultrasonic Flow Measurement for Industrial Applications, Dipl.-Ing., Friedrich Hofmann, KROHNE Messtechnik GmbH & Co. KG, April 2001. http://www.investigacion.frc.utn.edu.ar/sensores/Caudal/HB_ULTRASONIC_e_144.pdf; Arrangement: FLOWSIC600. Courtesy of KROHNE AG & Sick AG.*

flow profile then it will be symmetrical about the center line. So, by putting the necessary number of transducers across the pipe cross-section it is possible to get quite close to the actual velocity profile to calculate the average velocity. However, when there is a nonfully developed profile, i.e., a distorted profile, then there will be a greater velocity on right hand side. So, with single or two-pair transducers a large part may not be covered, hence the true representative velocity profile may not be addressed. It is therefore advisable to allow the flow profile to settle over a longer distance before the measurement point is selected, i.e., to allow sufficient straight lengths.

6.2.3 ENTRAPPED GASES OR SOLIDS

When there are entrapped gases/solids or both then there will be an error in the meter reading. In many cases it has been found that the velocity is over read. When the meter is meant to measure single-phase fluid, the actual volume will be less than the full pipe and the meter will read the full volume, ignoring the small volume occupied by entrapped gas/solid and/or both. Another issue often overlooked is that the presence of entrapped gases/solids or both, will reflect and absorb some amount of energy (already mentioned earlier). This means there is attenuation of energy. When there are too many particles/solids present in the liquid, there will be beam scattering/dispersion. When the fluid ceases to be single phase, beam scattering may occur under bubble flow or mist flow conditions [5]. Also, on account of gases, there could be reflection from the liquid/gas boundaries and some may be absorbed. All these issues are causes of signal attenuation. The generally accepted upper limit for entrained gases is about 2% by volume and for solids is 1%–5% by volume. When the liquid is operating very near its boiling point, a small change or decrease in pressure would cause boiling and bubbles may appear. Bubble flow could appear with liquids operating close to their boiling point.

6.3.0 Features and Applications of USFMs

In this section the features and application areas of USFMs are discussed. Features include not only the advantages but also the limitations of USFM.

6.3.1 FEATURES OF USFMs

On account of its noninvasive nature and requiring no moving parts, this type of flow meter has some special features, such as being rather inexpensive for large pipe applications and having no pressure loss, Easy retrofit etc. We now look into the advantages of this meter type.

1. **Advantages:** The following points could be considered as advantageous points for USFM:
   - *Large size:* Suitable for large-diameter pipes. In fact, large size is actually an advantage for USFMs as it gets more time to complete traversing of the beam and hence better measurements result. Also, on account of its noninvasive nature it is comparatively less expensive when line sizes increase. This is not possible in many other meters such as mass flow meters;
   - *Invasiveness:* Clamped types are totally *noninvasive* and *nonintrusive*. Wetted transducers are slightly *invasive but nonintrusive*. Only the insertion type is intrusive. Therefore, practically no pressure loss is expected from the meter;
   - *Moving parts:* There is no moving part or nonmechanical meter, therefore there is no wear and tear and the life expectancy is longer;
   - *Fluid type:* Like a magnetic flow meter it can be used for almost all fluids, even corrosive ones as these can be used in a noninvasive manner. USFM can measure liquid without conductivity. Transit time USFM can measure steam, gas, in addition to liquids. Doppler effect meters can be used for slurry flow;
   - *Flow range and performance:* A wide range of velocities is normally covered.

Generally meters are highly repeatable and reliable, with good accuracy;
- *Reynolds number:* Unlike vortex meter USFM does not have any lower limit for Reynolds number. Therefore, low flow can be measured better when compared with vortex meters. Also, with sufficient numbers of transducer pairs the issue of change over from laminar to turbulent profile can be resolved;
- *Retrofitting:* With clamped-on transducers, i.e., noninvasive transducers, it is very easy to adapt the flow measurement in retrofit applications;
- USFM can operate for any pipe materials as long as it is conductive to sonic waves;
- *Installation time:* Weld-on transducers could be installed in existing pipes and there are special transducers available (e.g., Pana adapta plug of GE US transducers) which can be used as hot tap connections. Overall the installation time is rather low. In fact, some have hermetically sealed transducers integrated into the meter body (e.g., Flosic600 of SICK for gas flow)
- *Response time:* The measurement being totally electrical, the response time is very fast;
- *Power consumption:* Power consumption is low;
- *Diagnostics:* Most modern meters available are intelligent, with extensive diagnostic features;
- *Maintenance:* Low maintenance is necessary mainly because these are noninvasive meters without moving parts;
- *Custody transfer:* Approved for custody transfer and faces competition with turbine flow meters in custody transfer issue. USFM enjoys edge for extensive diagnostic features.

2. **Disadvantages:** The following are major limitations of USFMs:
   - USFMs are rather costly when compared with other meter types;
   - Flow profile severely affects flow measurement, especially when single pair transducers are used;
   - USFMs can measure the flow only in a full pipe. However, in a Doppler effect meter it is possible to measure the fluid in partial-filled condition, if the transducers are below the level of fluid but there may be measurement error;
   - Meter performance is highly affected in the case that there is the possibility of deposits in the pipe by the fluid, because it will lower the diameter of the pipe and bring about the inaccuracy.
   - Transit type meters must have clean fluid free from foreign matter. If any other materials are present and they have a different density it may bring about error in measurement. In Doppler effect flow meters there are lower limits set for the concentration and size of the solids and velocity of fluid.
   - Fluid should be acoustically transparent [5].
   - Dirt or gas present in fluid may affect the measurement accuracy.
   - Acoustic noise even above human perception level may affect the measurement accuracy.
   - There is some temperature restriction for US transducers to operate. This is around 100°C. However there are high-temperature versions for operation at very high temperature and pressure (>500°C and pressure ~1500 bar [38]). These are mainly used in gas flow measurements in oil and gas or utility areas for superheated steam measurements.

6.3.2 APPLICATION AREA OF USFMs

The application area for USFMs is quite wide, therefore these are described here.

1. Like electromagnetic flow meters, USFMs are considered for almost all kinds of fluid (liquid and gas) without restriction on minimum conductivity.
2. As stated earlier, Doppler effect flow meters find wide application in sewage and waste management system applications. Also they find applications in slurries and pipe line leak detector applications.

3. US technology finds its application in open-channel flow metering but in slightly different way as discussed in Chapter III.
4. Ultrasonic gas flow meters are insensitive to pressure, flow strokes, and vibration dirt in gas. Therefore, they find applications in cases where other methods fail to measure [38].
5. USFM meters find applications in custody transfer with large sizes and high accuracy.
6. For application, proper selection, and judicious comparison of its simplicity, highly precise and reproducible output.
7. USFMs find applications in the following industries. The listed industries include application areas of both types of USFM (the last few are for the Doppler effect type).
   - Chemical plants;
   - Petrochemicals;
   - Natural gas;
   - Utility stations;
   - Water treatment plants;
   - Process plants;
   - On/offshore production (inline);
   - Crude oil pipe (inline);
   - Refineries (inline);
   - Multiproduct pipelines (inline);
   - Sewage;
   - Mining slurry;
   - Concrete production;
   - Waste treatment plants.

6.4.0 Specification of USFMs

A brief specification of USFMs is presented here to indicate the normal operating conditions of USFMs, their performances, and other requirements.

6.4.1 SPECIFICATION OF DOPPLER TYPE USFMs

The specification of Doppler type ultrasonic flow meters, which are quite popular in sewage and waste management systems, is presented in Table V/6.4.1-1. *Here it is to be noted that the design pressure is applicable for the insertion version only. This may not always be applicable.*

TABLE V/6.4.1-1 Specification Doppler Effect USFM

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Liquids with gas/solids or both. Normally at least 100 ppm sonic reflectors of size 35 μm (however >25% size 100 μm)		
2	Temperature range	Up to 200°C even with remote transmitter		
3	Pressure range	Up to 25 bar (insertion type only)		
4	Velocity range	0.03–10 m/s standard possible up to 12.5 m/s		
5	Pipe size	>25 mm (small version from 0.6 mm for clamped transducer). On upper side 3000 mm		
6	Environmental condition	Ambient temperature: (−40)–85°C 95% relative humidity		
7	Measurement type	Doppler effect reflection		
8	Meter orientation	Full pipe; horizontal/vertical (upward flow)		Partial filling possible if sensor below level of fill

Continued

TABLE V/6.4.1-1 Specification Doppler Effect USFM—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
9	Connection & mounting details	Depending on applicability, flanged connection of required size especially for inline meters integral transducers. Transducer mounting type. Section 6.1.4 may be referenced		
10	Electrical output connections	½″NPT/ET ISO M20 or manufacturer standard		
11	Transducers types	Clamped on (standard/high temperature), wetted Doppler probe, insertion (version also)		
12	Materials of transducers	Depending on IP class and temperature could be aluminum (anodized also), stainless steel, nickel-plated brass, PVC, Teflon, nylon, and other possible materials		
13	Armor	Possible with zinc-plated steel		
14	Enclosure class	Transducer and monitor: Both IP66/67		
15	Electronics unit	Polycarbonate, stainless steel, brass, anodized aluminum		
16	Power supply	90–250 VAC at 48–63 Hz. Or 15–30 VDC		
17	Output	Pulse (9999)/4–20 mADC/Relay version/Digital RS 485/232 (MODBUS connection) or other Smart versions with HART protocol, Fieldbus communication (e.g., PROFIBUS/Foundation Field bus) available (e.g., Optisonic 3400 of Krohne). Some meters have MODBUS compatibility also		
18	Output function	Rate volume flow, velocity, electronic totalizer, remote transmission and other controls		
19	Display and key pad	Normally standard 1–4 lines standard LED or backlit LCD display and associated keypad soft touch tactile type available		
20	Diagnostic feature	Self-diagnostic features including diagnostic test before starting ups common		
21	Response time	Selectable from 5 to 60 s		
22	Accuracy	0.5% AR to 2% FSD standard		
23	Repeatability	0.5% AR possible		
24	Certification	Necessary certification from appropriate authority for hazardous application		
25	Accessories	Suitable clamps, fixing and alignment hardware		
26	Transmitter type	Remote mostly with electronic unit		

Continued

TABLE V/6.4.1-1 Specification Doppler Effect USFM—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
27	Transmitter accuracy	0.25% AR		
28	Transmitter Response time	<1 s		
29	Transmitter enclosure	IP65/66		
30	Special feature	If any to specify requirement		

6.4.2 SPECIFICATION OF TRANSIT TIME TYPE USFMs

The specification of transit time type ultrasonic flow meters is presented in Table V/6.4.2-1. These types of meters are not only used for clean liquids but also for gas applications. They are also used for custody transfer applications. Naturally there are many variations. In the specification maximum values mainly have been highlighted. These meters are meant to measure bidirectional flow.

TABLE V/6.4.2-1 Specification Transit Time USFM (Including Custody Transfer/Inline)

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Normally clean fluid		
2	Temperature range	Up to 70°C standard/550°C (for high-temperature version)		
3	Pressure range	Up to 275 bar even 360 bar possible. Gas application up to 1500 bar [38] Standard meters are available with ANSI 150/300/600 lb or up to PN40 (inline meters)		
4	Viscosity range	0.1 to ~2000 cSt		At high viscosity version
5	Velocity range	Depending on meter size may be as low as 0.4 to above 20 m/s. Liquid max >30 m/s. Flow range for different sizes starts from 0.5 to 160,000 m^3/h or more (range given for getting some idea)		
6	Pipe size	>25 mm to on upper side 5000 mm (different applications)		
7	Environmental condition	Ambient temperature: (−40)–70°C 95% relative humidity		
8	Measurement type	Transit time. Depending on meter size these could be single pair or multiple pairs of measurement		

Continued

TABLE V/6.4.2-1 Specification Transit Time USFM (Including Custody Transfer/Inline)—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
9	Meter orientation	Full pipe; horizontal/vertical (upward flow). For inline meters horizontal with sensor support (as necessary and possible)		Partial filling possible if sensor below level of fill
10	Connection and mounting details	CS/SS flanges of rating ANSI up to 600 lb or PN40. For transducer mounting type Section 6.1.4 may be referenced		
11	Electrical output connections	½″NPT/ET ISO M20 or manufacturer standard		
12	Transducers types	Clamped on (standard/high temperature), wetted probe Spool piece type		
13	Materials of construction	Transducer: Depending on IP class and temperature could be aluminum (anodized also), stainless steel, nickel-plated brass, PVC, Teflon, nylon and other possible materials		
		Tube materials: CS/SS		
14	Gas detection (inline version) and temperature detector	Top mounted transducer for gas detection and temperature detector to compensate for transducer expansions		
15	Enclosure class	Transducer and monitor: Both IP66/67		
16	Electronics unit	Polycarbonate, stainless steel, brass, anodized aluminum		
17	Power supply	90–250 VAC at 48–63 Hz. Or 15–30 VDC		
18	Output	Pulse (9999)/4–20 mADC/Relay version/Digital RS 485/232—(MODBUS connection) or other Smart versions with HART protocol, fieldbus communication (e.g., PROFIBUS/Foundation fieldbus) available (e.g., Optisonic 3400 of Krohne or Prosonic 93 of E + H)		
19	Output function	Rate volume flow, velocity, electronic totalizer, remote transmission and other controls		
20	Display and key pad	Normally standard 1–4 lines standard LED or backlit LCD display and associated keypad soft touch tactile type available		
21	Diagnostic feature	Self-diagnostic features including diagnostic test before starting ups common		
22	Turn down:	120–150:1 standard; custody transfer 75:1		
23	Accuracy	2% FSD to 0.5% AR standard for other functions 0.1% AR *uncertainty* 0.027% as per API		
24	Repeatability	0.5% AR or for other applications. See API MPMS chapter 5.8 also [39].		

Continued

TABLE V/6.4.2-1 Specification Transit Time USFM (Including Custody Transfer/Inline)—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
25	Certification	Necessary certification from appropriate authority for hazardous application		
26	Accessories	Suitable clamps, fixing, and alignment hardware		
27	Transmitter type	Remote mostly with electronic unit		
28	Transmitter accuracy	0.25% AR		
29	Transmitter response time	<1 s		
30	Transmitter enclosure	IP65/66		
31	Special feature	If any to specify requirement		

6.5.0 Inline USFM

The specification given in Table V/6.4.2-1 covers many data belonging to custody transfer meters and gas flow meters. All these meters are inline USFMs. Therefore, there is a great deal of importance attached to this type of flow meter and they have been discussed separately. Typical inline USFMs and their orientations are detailed in Fig. V/6.5.0-1.

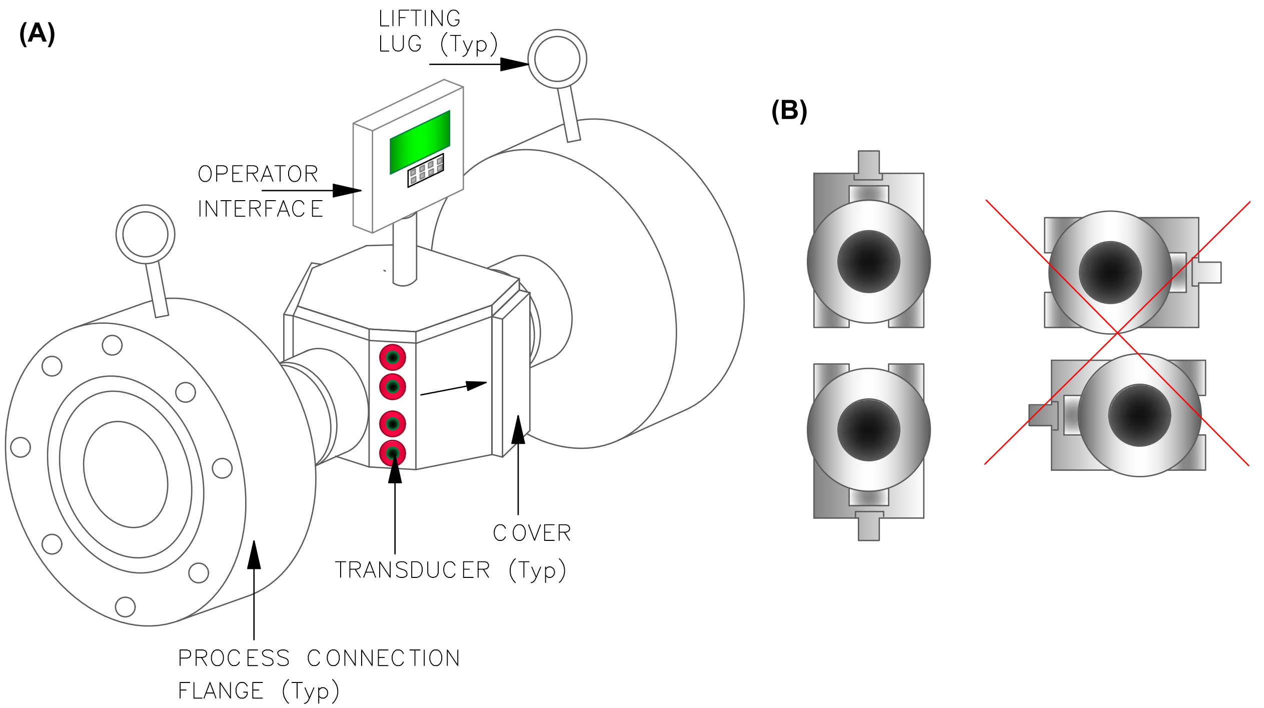


FIGURE V/6.5.0-1 Inline USFM. (A) Inline USFM parts. (B) Inline USFM orientation.

The inline USFM working principle is a transit time type. In the case of inline USFMs *normally* multiple measuring transducers are used to get rid of error due to change in profile and for better measurement accuracy.

6.5.1 FEATURES OF INLINE USFMs

Normally the following common but main features are attributable to inline USFMs:

1. Hermetically sealed US are used for inline meters;
2. Transducers are normally integrated in the meter body;
3. As these are wetted transducers, special materials like titanium or better materials are used;
4. There are a wide range of fluid Reynolds number restrictions—heavy crude, LNG;
5. Entrained gas detection for liquid application;
6. For large meters a direct path is used (similar to that shown in Fig. V/6.2.0-1);
7. Normally multiple (8−10) transducers are used;
8. With multiple transducers coverage is for flow profile to cancel any swirl;
9. Many can be used without flow conditioner (Chapter XI) with 5D upstream straight length;
10. Available in high-pressure/temperature/viscosity versions to cover all process conditions;
11. Pressure loss is very nominal, as there is hardly any intrusion;
12. Possible for over range;
13. High turndown ratio of 1:120;
14. All are provided with intelligent self-diagnostics and diagnostic tools;
15. High performance, i.e., accuracy, repeatability, etc.;
16. Most of these meters meet international standards (e.g., API) for performance requirements;
17. Intelligent interactive operator interface.

6.5.2 COMPONENTS OF INLINE USFMs

The following are the major system components of inline USFM.

1. **Meter body:** The meter body is complete with pipe sections on both sides. The meter is used for mounting of encapsulated transducers integrated with the meter body. The meter body may be a single piece casting or a forged one with suitable machining. The meter is connected to a pipe with the help of a flange connection. Normally the meter body is made from low-carbon steel or stainless steel.
2. **Process connection:** The meter body has flanges on both sides for connecting with associated pipes. Flanges are normally made up of stainless steel/low carbon steel of various ratings based on the application, typically available are ANSI 150/300/600 lb or more, or PN 10 to PN 64.
3. **Ultrasonic transducers:** Normally encapsulated ultrasonic transducers are made up of various materials including titanium. Transducers are put in the meter body, i.e., integrated with the meter body. Normally there will be multiple paths for eliminating errors due to profile changes and to obtain better measurement accuracy.
4. **Signal processing unit:** As indicated earlier, secondary electronics play a great role in the case of USFM. It is the main electronic unit responsible for proper functioning of the meter. All electronic blocks including switching power supply are part of the signal processing unit. To get an idea of this typical secondary electronics shown in Fig. V/6.1.5-1 may be referenced. A major function of the signal processing unit is to control the ultrasonic transducers by generating necessary oscillations of the US signal generation. It also analyzes the operator interface, and communication interfaces as described in Section 6.1.5 are other functions the signal processing unit performs.

There are a few requirements already mentioned at the beginning of Section 6.1.2 that should be taken into consideration while working on gas flow metering by US sensors.

6.5.3 BASIS OF CALCULATION OF VOLUME BY THE METER

Modern USFMs process the signal digitally and therefore sample the signal paths. Thus there are measurement cycles by which the gas velocity on each path is sampled. A typical such measurement cycle could be 10 times per second. One measuring cycle consists of a velocity measurement per path, the integration of the operating volume, several internal procedures, and updating of the measured value output channels [40]. There a few steps necessary to complete the flow computation. The steps indicated here are only some of the basic steps. For actual calculations it is better to consult the manufacturer's manual for all correction and calibrating factors. To limit the volume of this book only the following basic steps are explained:

1. **Transit time:** Determination of the transit time of the ultrasonic signals (already clarified earlier).
2. **Mean path velocity:**

$$v_{avi} = \frac{\sum_1^n vi}{N} \qquad \text{(V/6.5.0-1)}$$

   Here only valid (within measurement threshold) velocity signals are taken and also valid sample numbers are taken.
3. **Weighted average:** If there is multipath signal measurement then all paths naturally do not have the same relative weighting, so the weighted average will give a better result for average velocity, i.e.,

$$v_{av} = \sum_1^n wi \cdot v_{avi} \qquad \text{(V/6.5.0-2)}$$

4. **Volume:** In the next step the volume flow is calculated from the velocity by multiplying area.
5. **Profile factor correction:** To make the system calculation independent of the Reynolds number the profile factor correction is multiplied. For this, operating pressure is calculated by

$$P = \sqrt{P_{min} \times p_{max}} + 1\text{bar} \qquad \text{(V/6.5.0-3)}$$

6. **Flow correction:** Finally, the correction factor can be multiplied for the impact of pressure and temperature on the geometry of the meter body.
7. **Pressure and temperature impact on the geometry:** The flow calculations are on the basis of geometry parameters of the meter body for an ambient temperature of 20°C and 1 bar(a), so there may be the need for correcting the volume for different conditions.

   This is given by $Q_{v \cdot corr} = Q_v \cdot (1 + K_T (T - 293.15) + K_p \cdot p)$ where K_T stands for temperature coefficient related to meter material; for stainless steel it is $5.23 \times 10^{-5}\ K^{-1}$ f and K_p is around $6 \times 10^{-6}\ bar^{-1}$ [40].

6.5.4 MINIMUM BACK PRESSURE FOR INLINE USFM IN LIQUID APPLICATIONS

Since inline flow meters come in the main path of flow, they may be small but there would be some pressure loss. When inline flow meters are used in liquid applications it is necessary to prevent cavitations in the flow sensors. Therefore it is necessary that sensors are always fully filled and that there is enough back pressure not to cause flashing of fluid. Naturally, to calculate the minimum back pressure requirement it is necessary to know the vapor pressure of the process liquid. Therefore, the minimum back pressure must be greater than the sum of vapor pressure and pressure drop given in Fig. V/6.5.4-1. Such a manufacturer graph needs to be consulted.

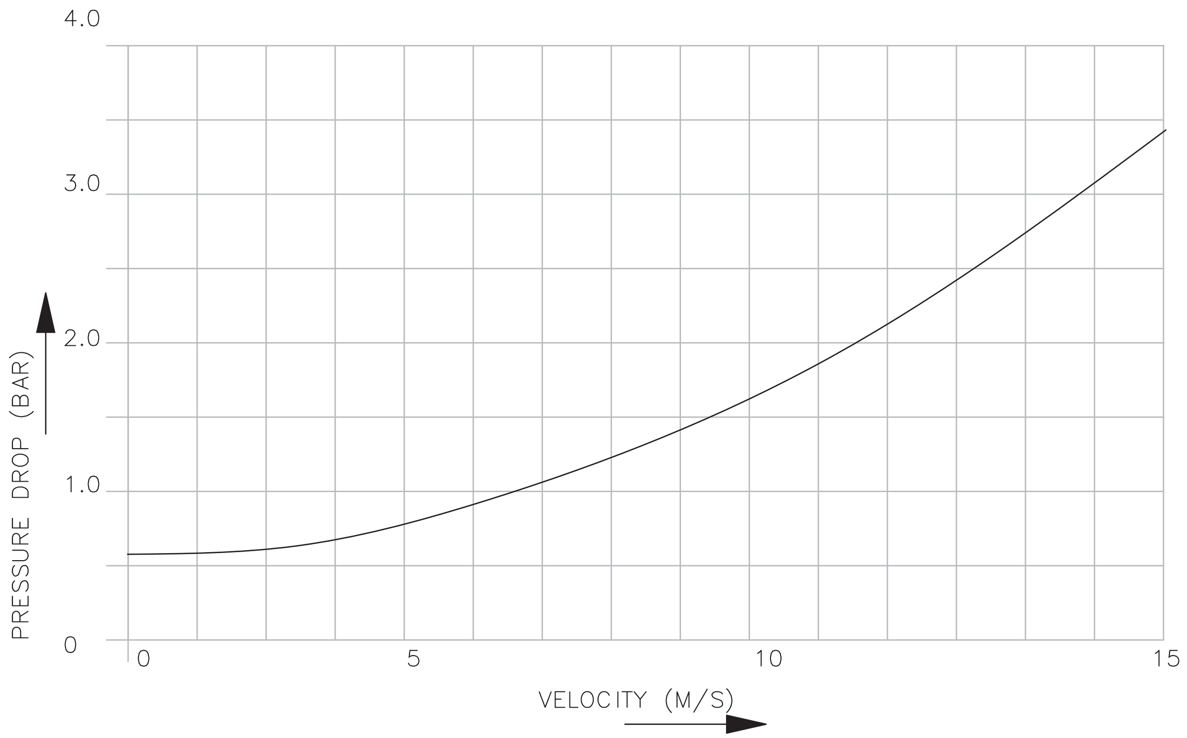


FIGURE V/6.5.4-1 Pressure drop for inline USFM (typical).

6.5.5 FLOW VELOCITY AND RANGEABILITY

Typical flow rate and velocity of an inline meter from a reputed company have been presented as Table V/6.5.5-1, to give an idea of the available ranges.

We now us take up the discussions on meter installations.

6.6.0 USFM Installation Discussions

USFM installation, especially for inline meters, requires checking the pipe diameters thoroughly and if necessary considering flow conditioners. Normally straight length 10D upstream and 5D downstream is necessary for meter/transducer installation. The discussions on meter/transducer orientations and spacing requirements have

TABLE V/6.5.5-1 Flow Rate and Velocity and Rangeability [40]

Meter Size (mmNB)	Velocity (m/s)		Flow (m^3/h)	
	Minimum	Maximum	Minimum	Maximum
150	0.4	30	27	2010
300	0.4	30	105	7880
500	0.3	30	200	20,280
600	0.3	30	300	29,580
900	0.2	25	450	56,670
1500	0.2	25	1280	160,090

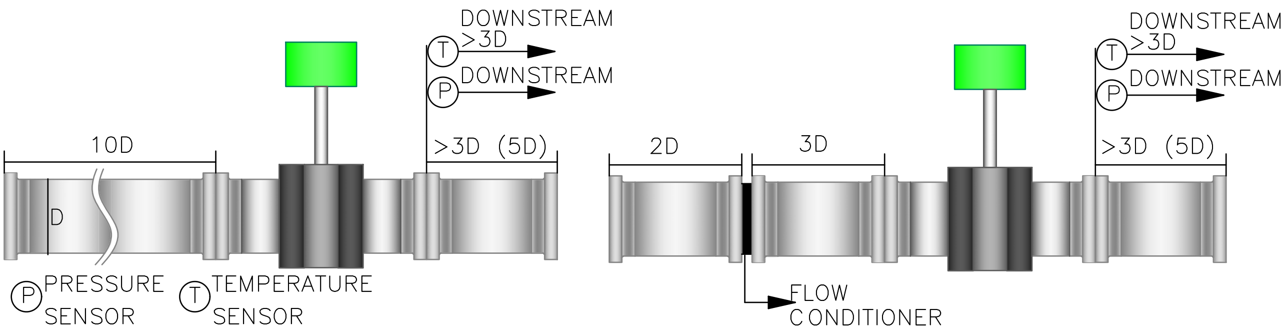


FIGURE V/6.6.0-1 USFM installation requirements.

already been covered (e.g., Section 6.1.4) and hence are not repeated here. However, when the flow conditioner (see Chapter XI) is used then the straight length requirements are reduced, as shown in Fig. V/6.6.0-1. As shown there, the pressure/temperature sensors should preferably be mounted in the downstream side. For large inline flow meters supports for transducer mounting are often required. Normally such supports are put at the transducer flanges. There is not much restriction on the point of placement of the pressure sensor in the downstream side but since the temperature probe has to come inside the pipe it is necessary that it should be placed at least 3D downstream.

From previous discussions it had been noted that the flow profile has a direct impact on the performance of the meters. Therefore, some upstream and downstream straight length requirements should be complied with to get proper meter performance. Table V/6.6.0-1 gives the straight length requirements. It is worth noting that the straight length requirements indicated below are essentially typical values and/or average values, as these parameters are dependent on pipe diameters.

It is necessary to follow the guidelines given by manufacturer, as each meter type may have different requirements.

6.7.0 Discussion on Meter Selection Process (Within the Same Meter Category)

The general flow meter selection procedure has been discussed at length in Section 4.0.0 of Chapter I. Within the same category of meter (e.g., ultrasonic meter) there will be a similar exercise one has to take up. Basically this exercise can be conceived as the marrying of the application requirements with various options available in the particular flow meter category, keeping in mind the budget and other application constraints. Here, in connection with USFM this has been discussed, but a similar exercise may be

TABLE V/6.6.0-1 Straight Length Requirements for USFM

Object/ Restriction	Upstream (D)	Downstream	Object/ Restriction	Upstream (D)	Downstream (D)
90 degrees bend	~20	10D	TEE	50	10
2 elbows in plane	25	5D	2 elbows out of plane	40	5
Reducer	10	5D	Valve	30	10
Pump	40–50	–	Diffuser	30	5

Distances: multiples of pipe internal diameter D.

done for other categories of flow meters and hence they are not repeated individually. Therefore, there are two major issues, i.e., options available and application requirements coupled with budget and application constraints.

6.7.1 OPTIONS AVAILABLE FOR THE FLOW METER CATEGORY

There are several ways one can look into USFM: measurement technology Doppler/transit time. Therefore, essentially it is necessary to understand how USFM can be classified. The following are the ways one can classify USFM prior to thinking about which one is suitable for a particular application.

1. **Measurement technology:** There are three techniques by which USFMs work. Of these only two technologies are more popular and these are:
   - *Transit time meter:* The principles of measurement of the technology have already been elaborated. Measuring methods also have some variations like direct type or reflective types. These are suitable for comparatively clean liquids, gas, and even for steam applications. These meters offer good accuracy. Major application areas include water (various types), sewage, process liquids, oils and petroleum, natural gas, etc.
   - *Doppler effect meter:* This is based on reflection of the US wave by suspended particles. The basic principle has already discussed at the beginning of this section. Here the major requirement is that liquid must have sonic reflective bubbles or solid particles (see point 1 in Table V/6.4.1-1). In this method insertion types are possible. Accuracy is moderate and the main application areas are sewage, waste water, effluent treatment plants, etc.
2. **Portability:** There are divisions in terms of handheld type, or fixed installation. In fixed installation there will also be variations, such as inline meter or transducer mounted on a pipe.
3. **Transducer type:** There are two kinds of transducers available, i.e., wetted type and clamp-on type. These are mainly applicable for cases where they are fixed with normal process pipes. However in the case of inline meters transducers are an integral part of the meter.
4. **Secondary electronics:** Secondary electronics is an important role in deciding the meter type. There are two types: conventional ones with pulse/analog or digital output or smart type. Smart version meters and associated computation power enable USFM to be selected as custody transfer meters. Ethernet compatibility and fieldbus support computing, and diagnostic capabilities are currently major issues in widening the selection options. The points discussed above pertain to the selection options available. One has to marry these options with the various requirements from mechanical and process aspects coupled with various constraints such as budget, installation constraints, harsh ambient, etc.

6.7.2 REQUIREMENTS AND CONSTRAINTS

We now look at requirement parts, i.e., the actual situation to find out the various requirements and constraints for the measurement application in question. Details given here is for USFM, but some these could be applicable for other meter types also.

1. **Pipe fill up:** Is the pipe full? If not, then a suitable installation solution to combat the situation may be tried or may opt for an insertion type Doppler effect type and/or consult the factory.
2. **Entrapped solids and gas:** Particle content and size, based on the situation discussed in Table V/6.4.1-1, flow technology type may be selected.
3. **Flow and velocity range:** Flow range and velocity range are major criteria for meter selection. From the above points the technology type may be selected, but the next important selection issue is dictated by this issue.

4. **Pipe:** Pipe size range, material lining (as applicable) are very important issues one should think about after deciding on the USFM meter size from the flow/velocity range. This is because it is related to the flowing medium, pipe size, and thereby the requirements of the reducer, etc. If there is a requirement then the question of available straight length becomes a selection point.
5. **Straight length:** Available straight length plays an important role in USFM; nearly 15D length is recommended as we have seen, and for installation this will be crucial.
6. **Temperature and viscosity:** Fluid temperature and viscosity will determine whether high-temperature/viscosity versions are to be selected. On the other hand, process pressure will dictate the selection between wetted type or clamp type (not applicable for inline type).
7. **Accuracy level:** A higher level of accuracy will determine multiple path type measurements. Inline meters are multipath measurements. Similarly flow cell solution is always more accurate than insertion type and would be a better option.
8. **Portability:** When portability is necessary clamp-on transducers could be a good option or the handheld type as used in HVAC could be the best choice.
9. **Output (smart version):** The type of output is another selection criterion. There are so many options available, such as analog output, pulse signal, digital output. Also, there are choices for a smart meter. Naturally, depending on the application and actual plant set up, such choices are important, e.g., for a situation where the ultrasonic metering package is complete with a data logger a simple RS 232/485 with a dedicated PC will do; on the other hand there are a number of USFMs and in the plant instrumentation is hooked up with fieldbus obviously to maintain uniformity and it is better to go for a smart device.
10. **Safety issue:** It is often required that the measurement be carried out in a hazardous location. Obviously people need to look for a device(s) with the necessary safety features and suitable certification from the appropriate authority. Many applications call for SIL (refer to the author's book [22] for details regarding SIL) so in such situations this is more applicable and is particularly applicable for oil and gas applications.
11. **Budget:** There could be a few other criteria, and the last BUT not least criterion is the budget. One has to cut one's coat according to the cloth. Even if very high quality is desired but the budget does not permit it one cannot go for that high-quality meter. Naturally there will need to be a compromise on some of the technical issues to meet the budget.

6.7.3 SELECTION DISCUSSIONS

It is critically important to prioritize the issues and then compromise. If even with some permissible curtailment of technical issues the budget can still not be met one will be forced to think on the budget. The question is now how to compromise on technical issues. Some issues cannot be compromised, e.g., if the application is in a hazardous condition requiring SIL certification (refer to the author's book [22] for details regarding SIL), as may be seen in oil and gas, safety certification cannot be sacrificed, instead one can think of compromising on the smart version because in the case of the smart version one may have to go for a safe fieldbus (refer to the author's book [22] for details regarding safe fieldbus) and cost might be reduced. This is just an example, one has to do the same judiciously.

Therefore, it is better to marry the options available with requirements using experts and experienced people in the field. Selection details have been elaborated for USFM, but this exercise is equally applicable for other meters also. Therefore, one has to jot down the various options for the meter along with application

requirements, and then marry them, keeping in mind the budgetary constraints.

6.8.0 Short Discussions on Calibration

There are a few steps necessary to cover the calibration of USFMs. However, each type of USFM may have a different calibration procedure. Calibration set up at the factory is not covered here. However, the following general steps may be followed as a part of good practices of calibration at the workplace.

1. **Verification:** Verification of the meters to check that the meter is meeting the requirements of specification and installation for the flow meter stipulated by the manufacturer.
2. **Test setup:** When there is a proper test facility, then USFM could be a good choice.
3. **Powering:** USFM to be powered and check the digital output signal through testing.
4. **Adjustments:** Determination of adjustment factors and check factory settings, and as necessary make new adjustments. Carry out a performance test to provide a flow rate within the valid flow range and check the performance.
5. **Mode selection:** To check various modes applicable for the meter for their functionality, including operational modes.

   Error limit: Check the sample flow to confirm that output is within the error limit specified.
6. **Set up:** The meter to be finally set for the actual case under configuration mode, i.e., parameters as applicable set up in the configuration mode.
7. **Set for operation:** After all parameters and data discussed above are done, the meter is switched off and taken for operation.
8. **Documentation:** All the results of observations as well as procedures should be properly documented.

6.9.0 Concluding Discussions and Recent Developments

Like a magnetic flow meter, this type of electrical flow meter based on US technology is a subject in itself. The system is so vast that a chapter could be developed on the same, especially on account of the many variations. However, we are limited by the volume of this book so we need to conclude the discussions on the flow meter. We do that by looking at recent developments in the area.

One of the major steps forward for USFM is its acceptance for custody transfer applications. On account of this, major players like Daniel, Krohne, and FMC technologies have come out with a number of meters with different advanced features. Major developments in the area include faster flow sampling rates, the new electronics platform, increased data set used available for computation of average velocity, allowing rapid recognition of changing flow dynamics [41]. With increased database power the user can get access to detailed flow parameters, including pressure, temperature, and gas composition, etc. Advanced electronic and computing platforms allow for better advanced calculations for auditing and invoicing. The audit trail complies with American Petroleum Institute Standard 21.1 [41]. The large database helps in reducing unnecessary fluid loss, lowering maintenance requirements, and energy savings. The meter operation is also optimized. Most of these meters also have high velocity and flow ranges. In addition, in the areas of communication and transmission there have also been substantial improvements. The advanced electronics of the Daniel meter support true 100BaseT Fast Ethernet connectivity. The majority of meters now available are HART-compatible and many of the meters from different manufacturers support fieldbus, such as Foundation fieldbus and Profibus. These are in

addition to the support of digital communication via RS 232/485 (MODBUS), etc. Development in the area of meter diagnostics is another recent development in USFM. New Diagnostics Software allows expert flow analysis, meter health checks, calibration cycle, etc. With the help of predictive diagnostics, it is possible to quickly detect and respond to abnormal situations to avoid process upsets and unscheduled downtime. Further applications and utilities pertinent to USFM have been presented in Chapter XII.

We now conclude the discussions on USFM and discuss anemometers.

7.0.0 ANEMOMETERS

In Greek, the word anemos means wind and anemometer is derived from this. An anemometer is used to measure the speed of wind. According to the Merriam-Webster dictionary "an anemometer is an instrument for measuring and indicating the force or speed and sometimes the direction of the wind." Although from this definition, an anemometer is to be used for wind/air only, it can be used to measure velocity and hence flow of fluid, be it compressible or noncompressible (liquid). However, in the real world it finds its applications in air/gases. An anemometer can be used to measure the velocity and hence the flow of air or gases. Such measurements could be either contained flow measurements such as in a HVAC duct; or could be uncontained flows such as in atmospheric air flow. The most common use of the instrument is in HVAC applications. Apart from this, they can be used for measurement of gas flow in stacks. There are several types and categories of anemometer as detailed in Table I/3.1.3-1. Chapter I also describes short working principles of all these types of anemometers. Therefore, we start by discussing various kinds of anemometers with some details in this section. One thing that should be remembered is that anemometers are different from other process flow meters, i.e., these are mostly portable accordingly treatise on them will be different.

7.1.0 Mechanical Anemometers

Mechanical anemometers come in three basic types, cup type, vane type, and impeller type. Often the last two are categorized as one type.

7.1.1 CUP TYPE MECHANICAL ANEMOMETER

As shown in top left-most part of Fig. I/3.1.3-5, a cup type mechanical anemometer is the simplest one. This design was first developed by Dr. John Thomas in 1846 and later modified by a Canadian engineer, Patterson, in 1926. It consists of three or four hemispherical cups with each hemispherical cup mounted at the end of each horizontal arm. These horizontal arms (three or four) in turn are mounted on the top side of a vertical shaft at equal angles in the same plane. Since the cups are arranged symmetrically, especially for four cups, wind will always have one hollow cup in its direction and back in the opposite side to create a mechanical couple for rotation. Whenever there is air/gas flow in the horizontal plane in any direction this passes the cups and it turns them (cups). The number of turns of the cups will be directly proportional to the velocity of the air or gas. So, from this one can infer that a cup anemometer is insensitive to wind direction (so it is better to use the term speed in place of velocity!) and by counting the number of turns of the cup over a period of time, produce average speed of air/gas for a wide range of speed, i.e., cup revolution speed is proportional to air/gas speed. If the vertical shaft is connected to a tachometer wind speed can be inferred, so if the shaft drives a direct current (DC) tachometer, it will generate an output voltage that is proportional to the wind speed. With the help of suitable a voltage to current converter, it is possible to get remote transmission also for remote indications/recordings. The relationship between the speed of air/gas is referred to as the anemometer factor; it depends on the dimensions of the cups and arm. Normally three cups respond faster to wind with constant torque when gas flow is at 45°.

1. **Typical features of a cup type anemometer include but are not limited to the following:**
   - Low price;
   - Simple instrument and easily understood;
   - Flexible;
   - Active even when wind is in a more vertical direction up to 30 degrees.
2. **Typical specification details are as follows:**
   - *Cup materials:* Brass or polycarbonate;
   - *Arm:* Black-anodized aluminum;
   - *Bearing:* Stainless steel;
   - *Typical accuracy:* 2%–5%;
   - *Wind speed:* 0.5–90 m/s or 320 km/h;
   - *Output:* pulse, 4–20 mA DC (if applicable).

7.1.2 VANE TYPE MECHANICAL ANEMOMETER

The vane type is another type of mechanical anemometer. The vane type has been depicted in Fig. V/7.1.0-1 (left figure). When there is air/gas flow, it causes the vanes to rotate with an *angular* velocity which is proportional to the speed of the air/gas (flow). In this kind of meter the axis of rotation of the vanes must be parallel to the direction of air/gas flow. Therefore, for all practical purposes, this will be in the horizontal plane. If there is a change in the direction of flow then the vane rotation axis has to be changed or adjusted accordingly. In an HVAC duct or in mining ventilation ducts where there is no change in the direction of flow of air, vane anemometers find good applications. For portable unit or local readout the vane velocity is shown in a local indicator with the help of a gear-and-spring assembly. Modern read outs are in digital form. Also, in many cases the same unit is used for additional functionalities like temperature, humidity, etc. So, in modern meters magnetic or capacitive coupling is used to generate an electrical signal. In modern units there are local memory to store data and most of these have the facility to communicate data with any local PC or data logger via RS 232/RS485 (e.g., MODBUS). Some of the meters have a "hold" button to freeze the last output. There are a few other features like display illumination, maximum/minimum value display, and mean value calculation, volume computation.

1. **Specification:** Short specification of vane type meter (air velocity part only—other

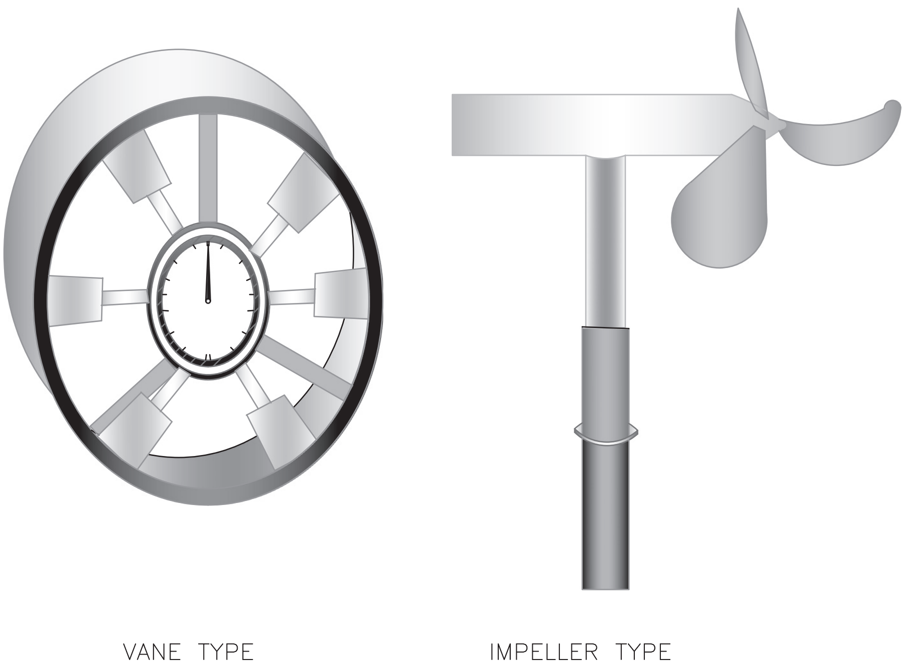


FIGURE V/7.1.0-1 Mechanical anemometer.

measurements could be humidity and temperature) are as follows:

- *Accuracy:* 1% AR ±1 digit;
- *Resolution:* 0.6–40 m/s;
- Operating temperature −20 to +50°C;
- Storage temperature −40 to +70°C;
- *Power:* Built-in battery with suitable battery life;
- *Display:* One- or two-line LCD back light;
- *Output:* Analog and digital;
- *Local memory:* For data storage;
- *Communication:* RS 232/485.

7.1.3 IMPELLER TYPE MECHANICAL ANEMOMETERS

The impeller anemometer is a measuring instrument for various wind-related parameters. Like the vane meter, impeller anemometers allow measurements of a few other parameters such as flow, temperature, relative humidity, dew point, etc. This is in addition to measurement of air/gas speed. This is a versatile environmental meter. In the impeller type anemometer the axis of rotation must also be parallel to the direction of the air/gas flow—hence horizontal The principles of operation is similar to that described in Section 7.1.2 hence not repeated again. When the direction of flow varies the axis has to follow its changes. Therefore, the meter can be used to measure air/gas speed as well as the direction of flow. The response speed of the meter is expressed in terms of the *length of wind* and is referred to as *distance constant* expressed in length unit. The typical value is 1.8 m. The meter shaft may be connected to a tachometer for indication.

1. **Specification:** Some specification data for an impeller anemometer (only speed measurement data) could be as follows:
   - *Speed range:* 0.2 … 30 m/s;
   - *Speed measurement accuracy:* ±3% AR ±0.3 m/s;
   - *Flow rate:* 0–9999 m^3/h;
   - Operating conditions 0 … + 50°C, RH <80%;
   - *Power:* Battery back up;
   - *Display:* One- or two-line LCD back light;
   - *Output:* Analog and digital;
   - *Local memory:* For data storage;
   - *Communication:* RS 232/485.

7.2.0 Thermal Anemometer—Hot Wire Anemometry

Basically, a hot wire anemometer is a kind of thermal flow meter discussed in Chapter VI. *Therefore readers are advised to go through the dispersion type thermal mass flow meter also.* A hot wire anemometer uses very fine wire (in the range of micrometers) which is heated up to a temperature above ambient. When air/gas flows past the wire it will take away some heat, so there will be some cooling effect. The rate at which it is cooled is proportional to the air (or gas) velocity at the probe tip. The electrical resistance of metal (e.g., tungsten/platinum) is dependent on temperature. In new types of thermistors wires are also seen, therefore it is possible to establish the relationship between the metal resistance or temperature with air/gas velocity. A hot wire anemometer can be classified as a constant power or constant temperature anemometer as discussed in Chapter VI. Hot wire anemometers have high-frequency response and spatial resolution. Of these two types, constant temperature hot wire anemometers are more popular because of their low electronic noise level and good high-frequency response. Also they have less chance of element burnt out if the air/gas flow suddenly drops and the constant temperature is maintained. On the other hand, they have slow temperature flow response and nonstable zero flow. For measurement, thermocouple/thermopile or bridge circuits could be used. Normally these are available in various ranges covering velocities from 0.1 to 10 m/s.

7.2.1 FEATURES OF THERMAL HOTWIRE ANEMOMETERS (HWA)

The following are the main features of HWA, including the advantages and disadvantages.

1. **Advantages:** The following are a few advantages an hotwire anemometer offers for velocity measurement.

- A hot wire anemometer is very good for measurement of velocity fluctuations in time domain in turbulent flows;
- Very good high-frequency response (up to 1 MHz possible);
- For wide velocity range; it is possible to measure velocity/direction and fluctuations;
- Low noise, i.e., high signal-to-noise ratio for measurement;
- Possible to carry out signal analysis both in time and frequency domain.

2. **Disadvantages:** The following are a few limitations of hot wire anemometers for velocity measurement.
   - This is an intrusive measurement with a modification possibility of local flow;
   - Not very sensitive to high turbulence;
   - Probability of wire burn out/breakage;
   - May not be suitable for hostile atmospheres;
   - For proper measurement a number of sensors are required.

7.2.2 DESCRIPTIVE DETAILS: HOTWIRE ANEMOMETERS (HWA)

1. **Operation:** A thin wire (~5 μm in diameter with active length about 1−2 mm) with resistance R_w is heated by current I to generate heat, I^2R_w. This wire is exposed to surrounding medium (air/gas) with velocity v. In equilibrium this heat loss must be balanced. When velocity changes the heat loss will be changed and hence the temperature will change. A new equilibrium will be reached at a new value. Active length is shown in Fig. V/7.2.0-1A. As stated earlier there are two modes, one is constant power, i.e., constant current mode, and the other is constant temperature mode.
   - *Constant current mode:* In constant current mode the current in the circuit is kept constant and resistance variation due to changes in temperature is monitored in a bridge circuit. As done in the case of a null balancing bridge circuit (similar to that used in the case of RTD), a servomechanism may be used. Whenever there is a change in temperature there will be a change in voltage drop across the resistance, R_w. This is monitored in the bridge circuit, and fed to the servo device. With the action of the servo device the arm resistances are changed to restore the current in the circuit.
   - *Constant temperature:* On account of the flow some heat will be taken away from the hot wire, and hence temperature will tend to fall. In this mode, the temperature and hence resistance of the wire is kept constant. Here also the bridge circuit is used and, with the help of a servo device, resistance in the bridge circuit is adjusted so that there will be a new current through the wire so as to restore the temperature at the hot wire. This temperature may be sensed by a thermocouple (T/C).

     Typical control schematic of the same is shown in Fig. V/7.2.0-1B. The schematic is a generalized one and not specific for constant current or constant temperature. The signal processing unit (SPU) amplifies and converts the small signal from the bridge circuit to a suitable signal level for remote electronics.

2. **Mathematical expression:** From the above discussions it is clear that there will be a change in energy.

$$\frac{dE}{dt} = W - H \qquad (V/7.2.0\text{-}1)$$

where E = thermal energy stored in wire $C_w \cdot T_w$; C_w = heat capacity of wire, and T_w = temperature of wire.

From the above $W = I^2R_w$; and H = heat taken away by the surroundings. When equilibrium is reached $\frac{dE}{dt} = 0$, hence $W = H$ and this is precisely done in the two modes of operation described. In arriving at such a mathematical conclusion a few assumptions are listed here:

- No radiation heat loss;
- Temperature is uniform over the active length;
- Fluid temperature and density are constant;
- Impinging velocity is small compared to that of sound;
- Velocity of the medium is normal to wire and uniform over the wire.

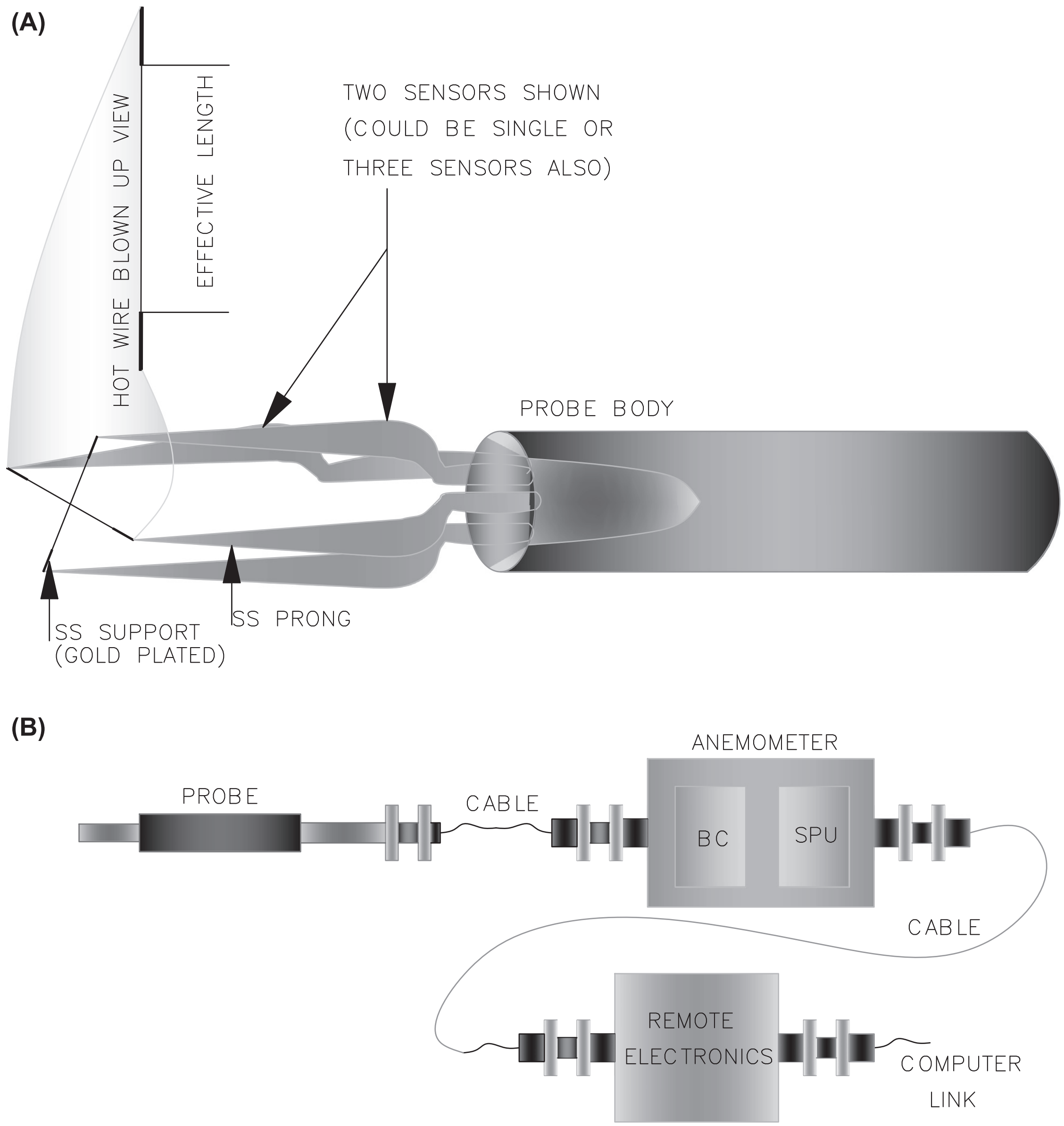


FIGURE V/7.2.0-1 Hot wire anemometer. (A) HWA block schematic. *BC*, bridge circuit (could be thermopile also); *SPU*, signal processing unit. (B) Hot wire anemometer probe.

3. **Probe types:** There are several ways probes can be classified. Based on the number of heat wires the probe can be classified as single wire (one dimensional—1D), two wires (two dimensional—2D), and three wires (three dimensional—3D). These are often referred to as single, dual, and triple probes. Various probe types and their features are listed in Table V/7.2.0-1.

Hot wire probes, be they 1D, 2D, or 3D, is supported by stainless steel prongs as shown in Fig. V/7.2.0-1A. Stubs or wire ends as shown in Fig. V/7.2.0-1A are part of the wire and may be gold-plated as indicated in Table V/7.2.0-1. Coated wire ends result in better mechanical and aerodynamic properties [42]. Hot wire provides nice performance in some applications but film is more robust than wire [42].

TABLE V/7.2.0-1 Hot Wire Anemometer Probe Types

Probe Type	Features	Remarks
Miniature wire	5 µm diameter; 1–2 mm long; platinum, tungsten	
Gold plated	At two sides gold plating active length ~1.25 mm	Accurate length; less heat dissipation
Fiber film	Hybrid film on thin quartz wire	Less wear, damage
Film	Metal film on quartz body	

7.2.3 SPECIFICATION OF HOT WIRE ANEMOMETERS

A short specification of a hot wire anemometer has been presented as Table V/7.2.0-2.

7.3.0 Doppler Effect Anemometer (Anemometry)

As the name suggests in this type of anemometry, the Doppler effect is utilized to measure the velocity of gas/air. This was first introduced in the 1960s by Yeh and Cummins. When sound or an optical beam travels into the flowing medium with nonhomogeneities, then the nonhomogeneities or particles in the measuring section of the flowing medium will reflect these beams. As seen earlier (see Section 6.0.1 in this chapter), due to Doppler effect, there will be a change of frequency of the reflected beam. The resulting Doppler shift in the returning frequencies can be related to the velocity of the flowing medium.

In a US Doppler anemometer velocities are derived from shifts in position between pulses, and the Doppler effect plays a minor role. If the particle velocity is at an angle of δ with the direction of detector then the governing equation is

$$v = \frac{F_d \cdot C}{2F_e \cdot \text{Cos}\delta} \qquad (V/7.3.0\text{-}1)$$

TABLE V/7.2.0-2 Specification of Hot Wire Anemometer (Velocity Only)

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Measurement	m/s, km/h, f/s, knots, miles/h		
2	Measuring range	0.2–20 m/s		Other unit adjust accordingly
3	Resolution	0.1 m/s		
4	Accuracy	+5% AR + LSB		
5	Probe type	Refer to Table V/7.2.0-1		
6	Sensing	1D, 2D, 3D		
7	Operating temp.	0–55°C		
8	Operating humidity	Up to 80% RH		
9	Display	12–13 mm LCD/LED		
10	Sampling	Manufacturer's standard		Typical: 1 s
11	Temperature measurement	Thermister		
12	Memory	Built in for min. max data		Recall facility
13	Power supply	Normal power supply with battery 9 V (typical)		
14	Port	Digital signal ports RS 232/485		For data logging
15	Auto off	Yes with manual button		

where F_d is Doppler frequency and F_e is the emitted frequency burst.

The ultrasonic Doppler effect has been discussed at length in a previous section and the measurement principle is similar, so there will be more focus on laser Doppler anemometry (LDA). The acoustic Doppler devices are more often used than the laser types. They are particularly useful in air pollution monitoring applications [9]. Although the LDA technique is discussed in connection with air flow measurement it is quite versatile, and it can be used to measure flow of steam (some applications), wind tunnel flow, fuel flow measurements, and in the design of internal combustion (IC) engine LDA offers many advantages over many traditional flow measurement techniques. In laser-based Doppler anemometers the intensity of the light scattered by the reflecting particles in the flowing medium is a function of their refractive index as well as their size (up to 5 μm). Here one should note that it is necessary to assume that the particle velocity is the same as that of the fluid. Such an assumption will be good as long as the particle sizes are under 5 μm. The LDA technique is discussed in the following section.

7.3.1 LASER DOPPLER ANEMOMETRY: GENERAL DISCUSSIONS

Prior to discussing the underlining principle of LDA, it is better to have some idea about the related terms and their interpretations. *Brief definitions/explanations of a few related terms are covered. This may be helpful for understanding and recapping of physics.*

1. **Laser Doppler effect anemometry:** Laser Doppler anemometry (LDA), is a technique in which the Doppler shift in a laser beam is used to measure the velocity in transparent or semitransparent fluid flows, or the linear or vibratory motion of opaque, reflecting, surfaces. This is often referred to as laser Doppler velocimetry (LDV).
2. **Coherent light source:** Coherent sources are those sources of light which emit continuous light waves of the same wave length, same frequency, and that are in the same phase or have a constant phase difference. For observing interference phenomena, coherence of light waves is a *must*.
3. **Light interference:** Interference in general is a process in which two or more waves of the same frequency (could be *light, sound, or electromagnetic* waves) either reinforce or cancel each other, the amplitude of the resulting wave being equal to the sum of the amplitudes of the combining waves. When two waves superimpose in such a way that their crest and trough match with each other, so that resultant waves have larger amplitude, it is called constructive interference. If two waves cancel each other then destructive interference will occur. Accordingly the fringe patterns will be produced.
4. **Fringe patterns:** An interference fringe or pattern results from constructive and destructive interference of light waves. Interference fringe is a bright or dark band caused by beams of light that are in phase or out of phase with one another.
5. **Laser characteristics:** Laser beam has two inherent characteristics, i.e., these lights are either monochromatic or very much pure in color and these light beams are inherently coherent.
6. **Bragg cell:** This is an acousto-optic component used with laser equipment to electronically control the intensity and deflection control of laser beam.

7.3.2 LASER DOPPLER ANEMOMETRY PRINCIPLES

From the above discussions it is clear that on account of the Doppler effect there will be a shift of frequency. In the case of LDA this means there will be change in the color of the light due to a shift in frequency. Doppler shift happens when the light is dispersed from the surface

of moving particles. *The Doppler shift in the frequency of a light source is proportional to the velocity of the dispersing particles.* Relative to the frequency of the light, this frequency shift is very small (from 1 kHz up to 0.1 MHz) [9] and cannot be measured directly.

In most LDA, single laser beams (e.g., He-Ne gas lasers or diode type solid state) are used to split it into two or more beams (often with color separation [43]). The mostly commonly used beam splitter is the Bragg cell as shown in Fig. V/7.3.0-1. The beams are focused through transmitting optics to cross perpendicularly to the particles in the stream.

At the crossing point, there will be interference due to the two beams crossing [44]. Therefore, there will be interference fringe patterns at the cross. The flow particles of the measurement section when passing through the cross will scatter the light beam of the interference pattern. This beam scattering is collected through the receiving lenses/optics and is focused on the detector. The detected signal is analyzed with the help of a photomultiplier at the detector to scan the signals. A *measuring volume* is defined by the light intensity distribution of the fringe pattern. The light intensity distribution then depends on whether a single reference beam or dual beam is used. A dual beam yields stronger measurement signal with less background noise, therefore In most cases of LDA the dual beam method is deployed as shown in the lower part of Fig. V/7.3.0-1. As a result, a typical fringe pattern has been shown. The distance d_f in the fringe pattern

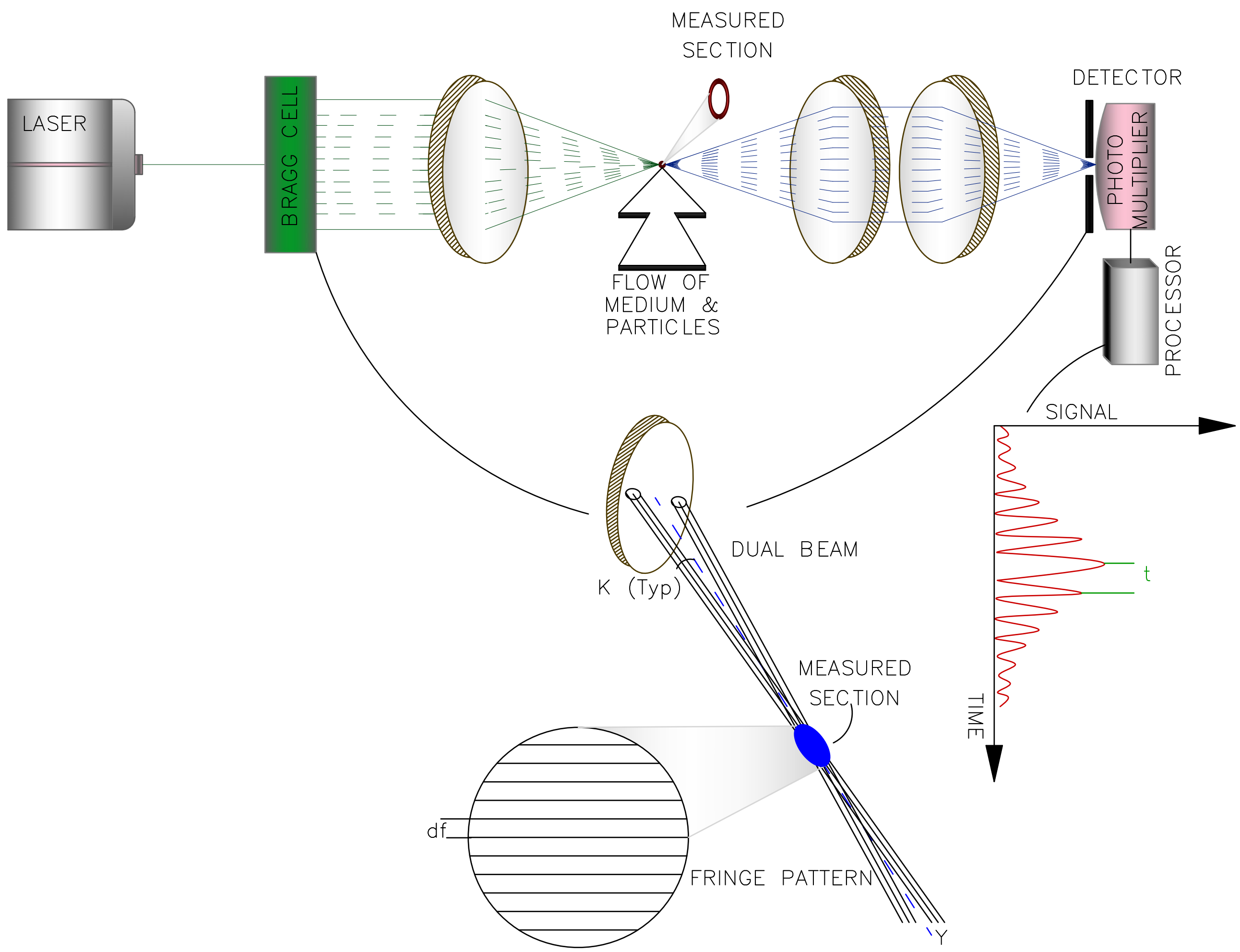


FIGURE V/7.3.0-1 Laser Doppler anemometry.

is a function of the beam angle K and the wave length of the incident beam (λ). This is given by

$$df = \frac{\lambda}{2\mathrm{Sin}K} \qquad (V/7.3.2\text{-}1)$$

When one sees the signal in the oscilloscope a signal pattern with varying amplitude will be seen and this is shown in Fig. V/7.3.0-1. Here time t represents the time needed for particles to pass between the known distance between two focused beams or in other words it gives the measurement of Doppler shift frequency. Therefore by multiplying Doppler shift frequency with the known distance d_f one can compute the velocity of the particle (hence the medium). So, the volume flow can be calculated from the intensity distribution pattern.

7.3.3 LASER DOPPLER FEATURES

1. When compared with the US Doppler effect, LDA measures contactless without any influence on the airflow. On the other hand, a US Doppler effect anemometer needs to be positioned into the flow—hence it is dependent on the room airflow structure.
2. The flip side of LDA is that it has limited focal length and needs complex optical arrangements, making it difficult to carry out measurement.
3. LDA is a method for velocity measurements in fluid dynamics and is applicable for fluid (gas/liquid).
4. This is an absolute measurement technique with no need for calibration.
5. Very high spatial resolution due to small measurement volume.
6. An important measuring technique for two-phase flow measurement (see Subsection 1.2.4.4 of Chapter IX) and measurement of dust cloud (see Section 1.2.0 of Chapter XII).

7.3.4 SPECIFICATION FOR LASER DOPPLER ANEMOMETERS

Short specification of LDA has been presented in Table V/7.3.4-1 to conclude the discussions on flow measurement by velocity and explore flow measurement by force sensing i.e. Target flow meter.

TABLE V/7.3.4-1 Short Specification for LDA (*Typical Data From Reputed Manufacturer*)

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Laser wave length	∼ > 500 nm		
2	Laser type	Solid state diode/gas		
3	Laser power	In the order of mW		
4	Velocity range	(−)300−1600 m/s	Note:−ve for direction	
5	Accuracy	< ±0.2% FSD		
6	Repeatability	0.05% FSD		
7	Droplet size	0.5−1000 μm		
8	Lens option	Manufacturer standard		
9	Processor BW	175 MHz		BW: Bandwidth
10	Sampling	8 bits		
11	Signal to noise	6 dB(min)		
12	I/O	Analog and digital quantity manufacture standard		

8.0.0 TARGET FLOW METERS

A target flow meter is also known as a drag flow meter from construction point of view. Target of this flow meter can be conceived as opposite of orifice. One may compare this with Krell's orifice discussed in Chapter II. The main difference is that here force is measured, not DP. A target flow meter is a kind of flow instrument to measure fluid flow rates with the help of the drag force to be exerted on a sharp-edged disk centered in a flow path due to differential pressure created by fluid flowing through the annulus. It is customary to place the target/disk mounted on a bar, with the axis of the target/disk coinciding with the axis of the flow path. The drag force is measured by a secondary device attached to the bar. On account of flow, there will be velocity of the flowing medium, so, when the flowing medium strikes the target the velocity energy is converted into pressure energy. This pressure will exert force on the target which is calculated by the target area multiplied by pressure converted by the velocity head. In this connection, Eq. (I/3.1.3-12) may be referenced. It has also been depicted in Fig. V/8.0.0-1.

8.1.0 Operating Principle

With reference to Subsection 3.1.3.7 in Chapter I, it has been noted that the target flow meter mainly operates in two ways, by measuring force directly by strain gage or by the deflection method.

8.1.1 TARGET METER WITH FORCE MEASUREMENT

In this method the dynamic force of fluid flow, i.e., velocity head of the flowing medium when hitting the target is sensed as a drag force. The target is inserted into the flow stream as shown in Fig. V/8.0.0-1. When the velocity head of the flowing medium gets obstructed by the target, the velocity head is converted into pressure head. This pressure based on the target area exerts force on the target. This is something similar to a Pitot tube where pressure is measured, instead here force is transmitted by a lever rod and flexure tube to a strain gage force transducer. The strain gage is connected to a bridge circuit which converts force due to the target sensor into a directly proportional electrical output. So, as seen from Eq. (I/3.1.3-12) (Force $F = C_d \cdot \rho \cdot v^2 \cdot A_t/2$), it can be seen that force is proportional to the square of velocity, and so strain gage output is also related to the square relationship. This has been shown in Fig. V/8.0.0-1 (top right side). Thus square root extraction is necessary. The electrical output is barely affected by static pressure. Since the meter does not have moving parts there is less wear and tear. Drag coefficient-based target flow metering is normally applicable for Reynolds numbers between 2500 and 250,000. It is worth noting that the square function of velocity with force is valid for turbulent flow only. If the meter is calibrated for turbulent flow then used for laminar/transition flow, the relationship is no longer valid. In such cases calibration data from the manufacturer should be obtained.

8.1.2 TARGET METER WITH DEFLECTION

In this principle, the target in the form of a diaphragm plate is inserted into the pipe. A flat torsion spring acts simultaneously as a mount for the paddle/target and also an elastic force. The paddle type target comprises a diaphragm plate and a lever arm. When the approaching stream strikes the diaphragm, it is moved by the flow in the flow direction, the lever arm is *deflected* by the force of the leaf spring. This *angular motion* is transferred noncontacting through the casing wall by a magnet sensing mechanism. This could be a Hall effect sensor with no losses. The signal from the sensor is processed in associated electronics for local display and remote transmission. The device thus operates with almost no wear. It is possible to implement different measuring ranges and instrument sizes by modifying the geometry of the lever arm, the diameter and shape of the diaphragm plate, as well as the height and thickness of the leaf spring.

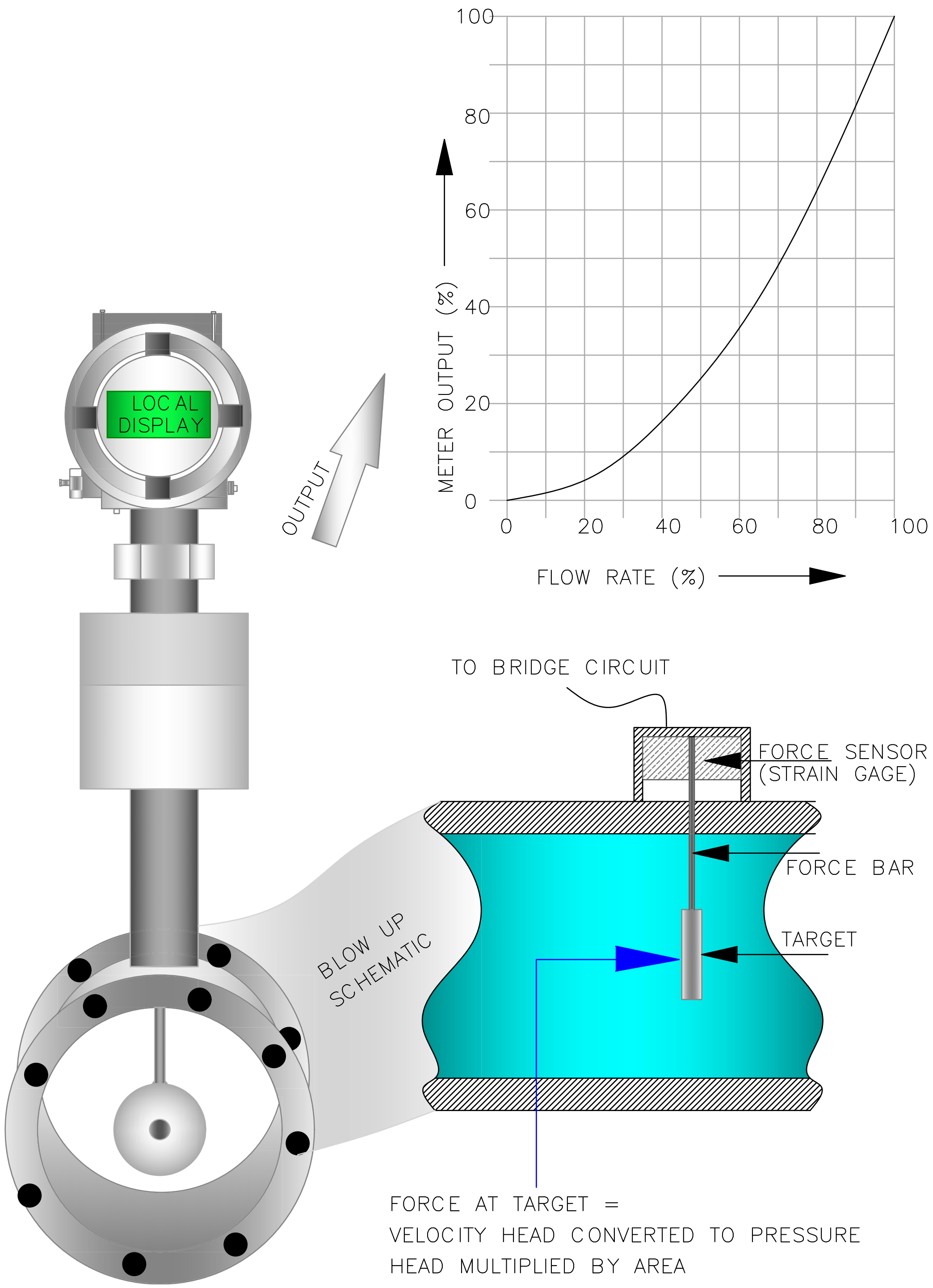


FIGURE V/8.0.0-1 Target flow meter.

8.2.0 Features and Applications of Target Flow Meters

In this section brief discussions will be given on the advantages, disadvantages, and application areas of this meter. We start the discussions with the features offered by the meter.

8.2.1 FEATURES OF TARGET FLOW METERS

These meters are available in various designs, such as wafer design, flange design, screwed connection, or in flare tube designs. They are also available in insertion and retractable designs.

Meters are available with a turndown of 20:1. The following are a few advantages and disadvantages of target flow meters.

1. **Advantages:** The following are major advantages of this meter:
   - This meter does not have any moving parts so wear and tear is reduced;
   - The meter can be used for any type of fluid and can be used for steam and cryogenics also;
   - The meter is very reliable with a prolonged life cycle;
   - Meters are available from very small pipe sizes, such as 12 mm up to 1.2 m;
   - Range/fluid changes are accomplished by simply changing targets;
   - Turndown of 20:1 is achievable;
   - Wide ranges of materials are available as materials of construction, such as 303/304 SS, 316 SS, Hastelloy, and Inconel.
2. **Disadvantages:** The following is a major disadvantage of the meter:
   - Field calibration is necessary.

8.2.2 APPLICATION AREAS OF TARGET FLOW METERS

As stated earlier, there is wide area of applications of the target flow meter as it is suitable for measurement of different kinds of fluid. There is a type of target flow meter referred to as the target variable area flow meter developed by Spirax Sarco, USA. This flow meter has been especially developed for steam flow measurement. It has been discussed separately in Section 8.3.0 of this chapter. Since the target flow meter detects the flow based on average velocity, and its axis coincides with the pipe axis, it allows uninterrupted flow of extraneous material (e.g., solids in liquid) or condensates below the target, i.e., at the bottom of a pipe. Similarly it allows unimpeded flow of gas or vapor along the top of the pipe. This flow meter is suitable for measurement of highly viscous fluid like heavy fuel oil and low-sulfur heavy stock oil in furnace oil for boiler applications. Use of target type flow switch is common (say) in fuel oil line.

8.3.0 Target Variable Area (TVA) Flow Meter (Courtesy: Spirax Sarco)

The target variable area flow meter by Spirax Sarco is specifically designed for steam flow measurement. The discussion begins with a short description of this meter.

8.3.1 DESCRIPTIVE DETAILS OF THE TARGET VARIABLE AREA FLOW METER

In line with the measuring principles of a target flow meter, this flow meter measures steam flow by measuring the force produced on a moving cone by the fluid flow. The strain thus produced is then converted into density compensated mass flow rate. A typical target variable area flow meter is shown in Fig. V/8.0.0-2. This meter has a special design. The cone can retract or extend based on flow quantity. When there is low flow the cone retracts and there will be a smaller annular orifice with an increase in low flow sensitivity. In contrast, with high flow the cone extends and there will be a larger annular orifice and flow capability will be high. Based on the flow, the cone retracts or extends; therefore, this is referred to as a moving cone [45]. The meter works on target flow-measuring principles with variable area at different flow ranges so it is referred to as a target variable area flow meter.

The meter consists of a meter body with a moving cone and meter stem. The moving cone is inserted into the pipe. Through the meter stem the electronic housing is connected to the meter. Normally the meter is provided with a built-in temperature compensation unit to take care of density variation. Currently these meters are available to cover the entire steam flow range.

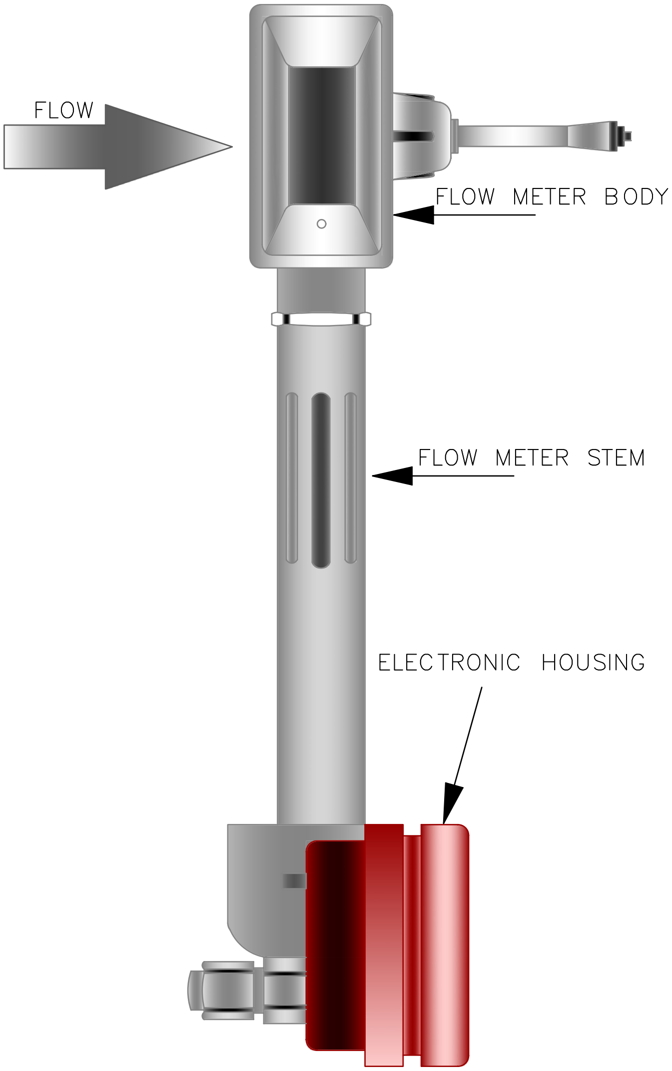


FIGURE V/8.0.0-2 Target variable area FM. *Developed based on TVA of Spirax Sarco. Courtesy: Spirax Sarco.*

8.3.2 FEATURES OF TARGET VARIABLE AREA FLOW METERS

The following are a few features of TVA worth noting:

1. High turndown ratio of up to 50:1 [46];
2. On account of linear relation between output signal and flow rate;
3. Accuracy does not suffer at a low flow rate [46];
4. In-built automatic inline density compensation;
5. Easier, low-cost installation;
6. Reduced straight pipe requirement.

8.4.0 Specification Details

8.4.1 SPECIFICATION FOR TARGET FLOW METERS

The specification for a target flow meter is as given in Table V/8.4.1-1.

TABLE V/8.4.1-1 Specification for Target Flow Meter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid	Liquid and gas		
2	Flow range	05–2000 L/min		
3	Size	DN 15 to 150		
4	End connection	Flange/wafer/screwed/insertion/retractable		Flange rating as per application
5	OP pressure	40 Bar (g)		OP: operating
6	OP temperature	(−)20–90°C		OP: operating
7	Materials of construction	Carbon steel/stainless steel. Also PVC target with internals available. Some offer brass version also		
8	Straight length requirement	Upstream 10D and downstream 5D		
	Accuracy	±3% FSD		
9	Repeatability	±1% FSD		
10	Sensing	Strain gage for force type. For deflection type magnetic sensing		
11	Output	4–20 mADC/Digital serial interface		
12	Display	Digital		
13	Operator interface	Front panel		
14	IP Rating	IP 65/NEAM4X		

8.4.2 SPECIFICATION FOR TARGET VARIABLE AREA FLOW METERS [45,46]

The specification for a target variable area flow meter is as given in Table V/8.4.2-1.

With this, discussions on target flow meters, i.e., flow measurement by force, are concluded. However, there is a comparatively newer but *proprietary* technique of flow measurement by SONAR which measures the volumetric flow by velocity measurement. The flow measurement approach and technique in this proprietary method is quite different from other conventional methods.

TABLE V/8.4.2-1 Specification for Target Variable Area Flow Meter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Type	Mass flow measurement		
2	Fluid	Saturated/superheated steam		
3	Size	DN 50 to 150 (100)*		*Sh. steam
4	End connection	Flange (international standard)		

Continued

TABLE V/8.4.2-1 Specification for Target Variable Area Flow Meter—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
5	OP pressure	32 Bar (g)		OP: operating
6	OP temperature	239°C		OP: operating
7	Straight length requirement	Upstream 6D and downstream 3D		
8	Accuracy	±2% AR		
9	Density compensation	Built in		
10	Output	4–20 mADC/Digital serial interface		
11	Display	Digital		
12	Operator interface	Front panel		
13	IP rating	IP 65		
14	Installation and commissioning	Menu drive from front panel		

Courtesy: Spirax Sarco.

They are deployed in offshore oil and gas production and other industrial flow metering systems. A brief account of these meters has been presented in the following section to keep the reader updated with this modern technique.

9.0.0 SONAR FLOW METER

(*As this technique is a proprietary technique details given here are as per the details available from manufacturer's literature*.) This flow measurement system is noninvasive and nonintrusive, and hence there is no pressure loss. This technology, as claimed by the patent holder Cidra (Sonartrac), is a new class of industrial flow meters utilizing measurement principles that are distinct from all conventional flow meter technologies [47]. The flow meter technology could be used for single/two-phase media also.

It is quite some time since SONAR was first used as a technique for underwater applications. However, Cidra developed this proprietary technique for flow measurements for offshore oil gas production. Later the same technique was utilized for other industrial flow measurements also.

9.1.0 Basic Measurement Principle

In SONAR flow measurement techniques two sets of sensing techniques are deployed in synergistic measurement techniques. The first and most vital technique measures volumetric flow rate by monitoring turbulent "eddies" within the process flow. In order to assess the compositional information about the medium, the second technique measures the speed at which sound propagates through the medium.

9.1.1 VOLUMETRIC FLOW

Turbulent pipe flows contain self-generating coherent vortical structures, often termed "turbulent eddies." Brief details regarding the formation of turbulent eddies have been elaborated in Subsection 1.2.2.6 in Chapter I. These eddies remain coherent for quite some distance in the downstream side. They breakdown into small eddies till they dissipate the entire energy. "*SONARtrac* flow meters use a patented approach, based on well-established and mature sonar array processing techniques, to measure the velocity of these turbulent eddies as they convect

past an array of sensor" [47]. Sensor array detects the pressure fields associated with the movement of eddies, and *SONARtrac* flow meters determine the speed at which these eddies travel past the array of sensors. The volumetric flow rate is determined using a Reynolds number-based calibration procedure, which links the speed of the coherent turbulent structures to the volumetric flow rate [47]. The arrangement for this has been depicted in Fig. V/9.0.0-1A.

Let us look into the details of measurement. The vortices in a pipe have a broad range of sizes, which are bracketed by the diameter of the pipe on the largest vortices and by viscous forces on the smallest vortices [48]. As discussed above, all these vortices are distributed over the entire cross-section of the pipe. As shown in Fig. V/9.0.0-1B velocity is measured by tracking the vortices in the following sequence.

- The turbulent eddies or density variations create a small pressure change inside the pipe wall, resulting in a dynamic strain as shown in Fig. V/9.0.0-1B, sensed by the passive sensor wrapped around the pipe.
- There are an array of such sensors to detect such changes. These sensors are spaced at precisely a set distance from each other along the axial direction of the pipe.
- The electrical signal from each sensor element is interpreted as a characteristic signature of the frequency and phase components of the disturbance under the sensor.
- An array-processing algorithm combines the phase and frequency information of the characteristic signature from the group of sensor array elements to calculate the velocity of the characteristic signature as it propagates under the array of sensors [48].

9.1.2 FLUID COMPOSITIONAL DETAILS

At the initial stage of the discussion it was stated that there are two sets of measurement. The first was for measurement volumetric flow as discussed above. Now, the second technique, the speed of sound through the medium/fluid, is measured to get the information about the compositional details. With the help of measurement of the speed of sound through the fluid, it is discovered whether the fluid is single or multiphase. Therefore, it is possible to deploy the technique for fluid flow measurement in single as well as multiphase fluids. According to the claim by the manufacturer "This approach is particularly synergistic with the *SONARtrac* volumetric flow meter in that the sound speed measurement and the phase fraction measurement can often be recorded using the same hardware required for the volumetric flow measurement. For example, in a two-component mixture, with knowledge of the density and sound speed of the two components, the measured sound speed can be used to determine the volumetric fraction of the two components" [47]. As we are aware, the speed of sound can be deployed to determine the oil/water fraction in oil and gas applications, entrapped air in pulp slurry, or wetness of saturated steam, etc. Thus with the help of the second technique, in conjunction with the first volumetric flow measurement it is possible to find the individual volumetric quantity in two-phase flow. Use of SONAR in multiphase slurry flow measurement has been discussed in Section 3.3.0 of Chapter VII.

9.2.0 Features and Application Areas

A few features and application areas of this meter from the literature are listed below.

9.2.1 FEATURES

1. **Velocity range:** velocity range (3 to 200 f/s) between 0.9 to 60 m/s;
2. **Available sizes:** Pipe size (2−60 in.) 50−1500 mm;
3. **Pressure loss:** Nonintrusive, hence no pressure loss or obstruction;
4. **Reliable:** Reliable and no chance of clogging;
5. **Corrosion and coating:** There is no chance of it becoming corroded by corrosive chemicals like high-temperature acid. Also, there is no possibility of coating as is common in magnetic flow meters in many slurry applications;

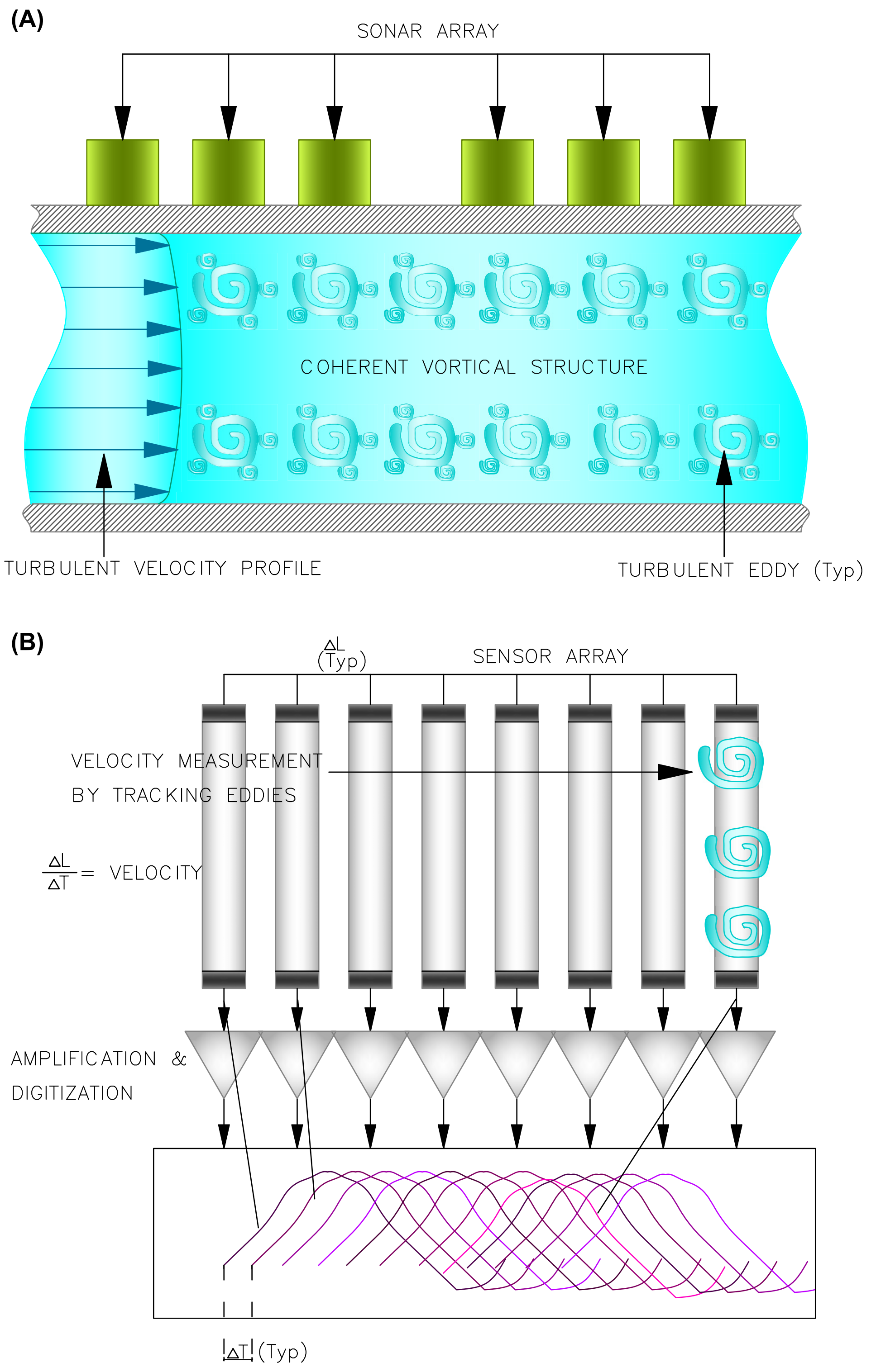


FIGURE V/9.0.0-1 SONAR flow metering. (A) Turbulent eddies and sensing. (B) Induced strain for turbulent eddies and velocity sensing. *(A) Adapted from SONARtrac® Flow Meter Technology — General Concepts, Cidra, 2017. https://www.cidra.com/sites/default/files/document_library/BI0011_SONARtrac_General_Concepts.pdf. Courtesy: CIDRA. (B) Adapted from P. Rothman, C. O'Keefe, A. Thomas, Application of Unique Sonar Array Based Process Monitoring Measurement Equipment for Minerals Processing Applications, CiDRA Minerals Processing and Krohne Mining & Metals Processing, BI0407 Rev A, 2009. http://www.cidra.com/sites/default/files/document_library/BI0407_Application_of_Unique_SONAR_7-15-09_Final.pdf. Courtesy: CIDRA & KROHNE.*

6. There is no chance of leakage through the flange;
7. **Detection leakage:** It is possible to detect changes in process operation due to leakage of gas, etc. and to detect changes in process performance;
8. Easier installation as sensors are clamped type.

9.2.2 APPLICATION AREAS

Some of the application areas are as follows:

1. Offshore oil and gas production;
2. Multiphase flow and wet gas measurement (Chapter IX);
3. Pulp and paper industries;
4. Power generation;
5. Food and beverage;
6. Water and wastewater treatment;
7. Chemical plants.

9.3.0 System Specification [49]

A short specification of the SONAR flow metering technique has been given in Table V/9.0.0-1 based on the manufacturer's data [49]. As this is a proprietary instrument, it is recommended to consult the manufacturer for actual application.

Now, we conclude the discussions on fluid flow measurement by measuring velocity and force. Next we look at discussions on fluid mass flow measurement techniques.

TABLE V/9.0.0-1 SONAR Flow Measuring Instrument (Volumetric Flow)

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Type	Volumetric flow meter		
2	Fluid	Single or multiphase		
3	Size	2–60″ (50–1500 mm)		
4	Sensor	External to pipe (sensor band of size 50 cm along axial direction wrapped around the pipe) dry fixing		
5	Operating temperature	100°C		
6	Velocity range	0.91–9.1 m/s		
7	Accuracy	±1% AR		
8	Repeatability	0.3% AR		
9	Output	4–20 mADC/Digital serial interface, pulse		
10	Smart transmitter	Supports HART, Fieldbus such as PROFIBUS/Foundation fieldbus		
11	Display	LCD backlit		
12	IP rating	IP 65		
13	Power supply	100–240 VAC 50/60 HZ; DC 18–30 V		
14	Hazardous application	Certified by appropriate authority		

LIST OF ABBREVIATIONS

ABS Absolute
AC Alternating current
ADC Analog to digital converter
AR Actual reading (in connection with accuracy)
CHU Constant head unit
CIP Clean in place
CMRR Common mode rejection ratio
CMV Common mode voltage
CS Carbon steel
DC Direct current
DP Differential pressure
DPT Differential pressure transmitter/transducer
DSP Digital signal processing
EMFM Electromagnetic flow meter
EPDM Ethylene propylene diene monomer (rubber)
ETFE Ethylene tetrafluoroethylene (type of plastic)
FSD Full-scale division (in connection with accuracy)
FTR Flow turndown ratio
GTFM Gas turbine flow meter
HFO Heavy fuel oil
HVAC Heating ventilation and air conditioning
HWA Hot wire anemometer
IC Integrated chip/internal combustion (engine)
ID Internal diameter
I/O Input/output
LDA Laser Doppler anemometry
LDV Laser Doppler velocimetry
LHS Left-hand side
LVDT Linear variable differential transformer
MFM (Electro) Magnetic flow meter
MHD Magneto hydrodynamics
MTR Measurement turndown ratio
MUX Multiplexer
NB Nominal bore
OD Outer diameter
PFA Perfluoroalkoxy alkanes
PTFE Polytetrafluoroethylene
PVDF Polyvinylidene fluoride—plastic type
RF Raised face or radio frequency
RHS Right-hand side
RTD Resistance temperature detector
RTJ Ring tongue joint
SIL Safety integrity level
SIP Sterilize in place
SS Stainless steel
T/C Thermocouple
TFM Turbine flow meter
US Ultrasonic/United States
USFM Ultrasonic flow meter
USFM T/D Ultrasonic flow meter transit time/Doppler
USRB United states Bureau of Reclamation
UVC Universal viscosity curves
VFM Vortex flow meter
VM Valve manifold
VTR Viscosity turndown ratio
WRT With respect to

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CHAPTER VI

MASS FLOW METER

Chapter Outline

1.0.0 INTRODUCTION AND GENERAL DISCUSSIONS

In most industrial plants mass flow information is preferred in technical processes for cost, material, and mass balance calculations. Also, mass flow measurement is the basis of most recipe formulations and custody transfer operations throughout the industry. Normally mass is an intrinsic property of the three states of matter. However, in the case of multiphase, or entrapped gas in liquid or solids in liquid and in a few other cases, this may not be valid. Mass is independent of physical influences like pressure, temperature, etc. Pressure, density, temperature, and viscosity do not change a mass. In view of this, most plant calculations are done on this basis. It is possible to arrive at mass flow from volume flow by multiplying the measured volume flow with the density at the operating condition. In this approach one needs to consider the following limitations.

- In many cases the correct fluid properties are not obtainable.
- When, for changing operating conditions, temperature and/or pressure compensations are applied and mass flow is computed in a flow computer, then all the inaccuracies of these measurements become multiplied and the overall measurement suffers greatly.

Thus, in view of all these issues, most plant calculations are done on this basis. As mass flow measurements are deployed for the most critical flow measurement applications in a processing plant, the reliability and performance of the mass flow meter is very important and critical. As explained in Chapter I, Section 3.1.4, mass can only be measured indirectly, e.g., with the help of Newton's second law. Therefore to get the mass flow, it is necessary to accelerate the fluid in a rotating system and measure the inertia effects. Alternatively, as shown in Section 3.1.4 of

Plant Flow Measurement and Control Handbook. https://doi.org/10.1016/B978-0-12-812437-6.00006-8

Chapter I one has to take the help of a thermal system to get the mass flow information. In this chapter detailed discussions will be presented on both these methods. Also, in the case of mass flow measurement by a mass flow meter based on the Coriolis principle, it is possible to get much more information from the meter as a corollary of the measurement principles. Other than mass flow, it is possible to measure the density, concentration (also concentration control), viscosity, and temperature. As well as the Coriolis method, there are several other mass flow measurement methods, however Coriolis is the most important, and possibly the most significant advancement in flow measurement over the past few years has been the introduction of the Coriolis mass flow meter which is continuing to gain popularity in industrial applications.

Frankly speaking it is not possible to measure mass flow directly. Mass flow can be detected by any of the following methods:

- Force (or torque) resulting from linear (angular) acceleration;
- Coriolis acceleration;
- Thermal method;
- Force (or torque) resulting from linear (angular) acceleration;
- Radiation method.

Various methods have been discussed in Section 3.1.4 of Chapter I. In this section these issues will be addressed at length. Of these methods, radiation methods are mainly used for bulk flow in solid flow measurement and such measurements have been covered in Chapter VIII. However, there are methods to measure fluid mass flow by combining a volumetric flow and radiation-type density monitor. In this method volumetric flow is measured by a volumetric flow meter, e.g., an electromagnetic flow meter, and density is measured by a nucleonic method. The signal from both devices will be combined to compute mass flow—hence this is not a true mass flow metering system. Looking from the application point of view, the Coriolis flow meter tops the list. Therefore, we start the discussions with the Coriolis flow meter.

2.0.0 CORIOLIS MASS FLOW MEASUREMENT

Prior to the discussions on the Coriolis mass flow meter we give a brief background discussion.

1. **Day-to-day experience:** Recall from your early school days that while being explained the rotational motion of the Earth, it was stated that if someone went to the North Pole and dropped an object, it would reach the ground at some distance away from where it was dropped. Another good example is why large storms have spinning effect. This also happens due to the Coriolis effect. In a large storm there will be an eye of the storm with low pressure. Therefore, the outside high-pressure air will flow towards the eye from all directions. On account of the rotation of the Earth due to the Coriolis effect, the path of gushing air will be deflected and will create a spin. If this is in the northern hemisphere then the spinning motion will be counterclockwise, while in the southern hemisphere it would be in a clockwise direction. Exactly on account of the same effect, if a person from the equator (*highest* speed due to *largest* diameter) starts walking towards the North or South Pole, that person's path will retain the higher speed (that they had at the equator) and a *slow*-moving North Pole person's path will be different from the targeted path (moving toward the east as the Earth rotates from west to east). So, the North Pole-bound path will be deflected towards the *right* and the South Pole-bound path will be deflected toward the *left*. Another good example would be two children sitting on a rotating platform in the same radial path. One is sitting midway between the axis and outer edge and the other is on the outer edge. If the child sitting inside throws a ball it will never reach the child sitting on the outer edge. This is also due to the Coriolis

effect. We need to note that in all such cases the frame of reference is rotational. Therefore, one can conclude that Coriolis happens in a rotational frame. This is *half true*. The Coriolis effect happens in the case of rotation as well as whenever there is OSCILLATION, which is of interest to us. So, let us now try to find the effect that influences such path changes as there must be a force which is behind these phenomena.

2. **Discovery:** Gustave de Coriolis, the French physicist and engineer (1792–1843), first discovered that in a rotational frame of reference there is some supplementary force. On account of this discovery such supplementary force was named after him and is known as Coriolis force. The physical effects on account of this force are referred to as the Coriolis effect. Coriolis force is applicable for rotational movement as well as any oscillating (vibrating) system.
3. **Analytical—conceptual:** There are a number of approaches to describing the dynamics of a vibrating tube conveying fluid. The analysis of the problem is quite complex, however, it can only be obtained for a simple system with an ideal tube conveying an incompressible and nonviscous fluid. For more complex systems, solutions can be found through approximations or using finite element methods [1]. However, here such analytical approaches are not covered as they are beyond the scope of this book. Instead, in the following section, a physical interpretation of the system will be looked into to understand the requirements and functioning of a Coriolis meter.

2.1.0 Coriolis Mass Flow Meter Theoretical Background

Coriolis industrial applications came to light sometime in the 1950s and the first Coriolis meter was built in 1970 [2]. In this section the main principles of operation of this meter will be discussed. However, prior to that, it is better to acquire some knowledge on the conceptual approach.

2.1.1 CORIOLIS FORCE CONCEPTUAL IDEA

1. **Coriolis effect on rotational applications:** The discussion starts with the Coriolis effect on rotational applications. Let us take a straight tube filled with fluid, then the pipe is rotated, at an angular velocity ω, around an axis as shown in Fig. VI/2.0.0-1A. As long as there is no flow of fluid (it is only filled) in the pipe, the fluid particles move on their respective orbits equivalent to the distance r from the axis of rotation. Therefore, at distance r_1, the tangential velocity of any particle would be $r_1 \cdot \omega$ whilst at another distance r_2, the tangential velocity would be $r_2 \cdot \omega$. These have been shown in the middle section of Fig. VI/2.0.0-1A and the directions of orbital velocities have been shown by red dotted lines. (General physical explanation by vector: *At this time only centrifugal force is acting. Therefore, at any point the general expression will be* $F_{centrifugal} = (-)m\overline{\omega} \times (\overline{\omega} \times \overline{r})$.)

   If the fluid flows in a direction from left to right, i.e., away from the axis, at any velocity v, on account of Coriolis effect in *rotational frame*, then as each mass particle moves, e.g., from r_1 to r_2, it will be accelerated (giving rise to a force for each mass) by an amount equivalent to its movement along the axis from *low to higher orbital velocity*. Naturally, such acceleration is in opposition to the mass inertial resistance and is felt as a force opposing the pipe's direction of rotation (because *orbital velocity is due to rotation*), i.e., it will try to decelerate the rotation of the pipe. For a better understanding this has been depicted in the top part of Fig. VI/2.0.0-1A. As can be seen there, blue continuous lines are actual rotation when there is flow, and these are *shorter* than the red dotted line to show deceleration. On the other hand, the flow is in a reverse direction, particles in the liquid flow moving towards the axis are forced to slow down from *higher to low orbital velocity* and the resultant Coriolis force

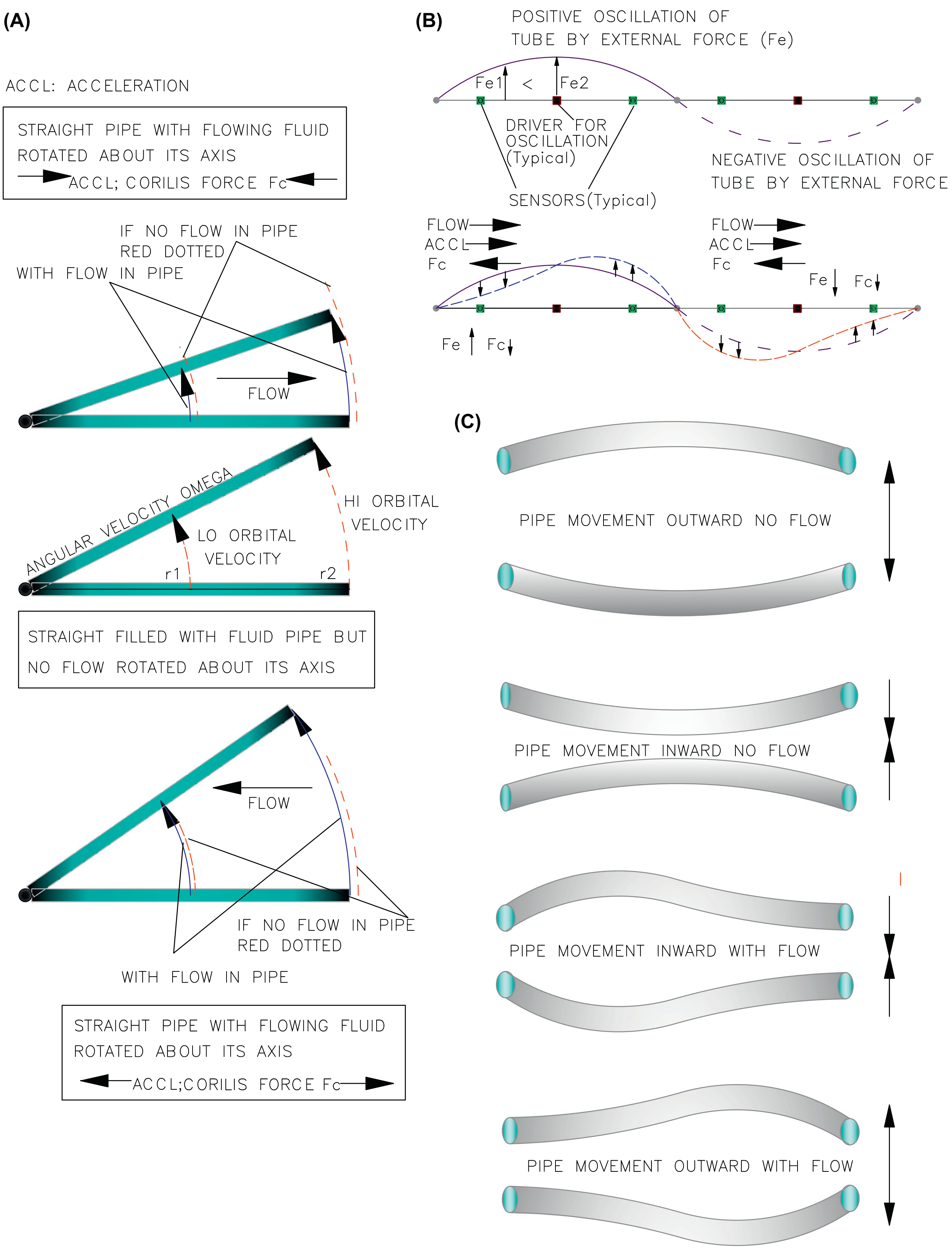

FIGURE VI/2.0.0-1 Concept of Coriolis force. (A) Coriolis effect for rotation. (B) Coriolis effect for oscillation. (C) Twin flow tube Coriolis meter. *Red dot*, light gray dot in print versions.

will try to accelerate the rotation of the pipe. The situation has been depicted in the bottom part of Fig. VI/2.0.0-1A. As can be seen there, blue continuous lines are the actual rotation when there is flow in the reverse direction and are <u>*longer*</u> than the red dotted line to show acceleration. (<u>General physical explanation by vector</u>: *Here the effective force will be given by centrifugal force and Coriolis force and the <u>general expression</u> will be given by* $F_{effective} = F_{centrifugal} \pm F_{Coriolis}$ *depending on the flow direction and is given by* $F_{effective} = (-)m\overline{\omega} \times (\overline{\omega} \times \overline{r}) - 2m\overline{\omega} \times \overline{v}$. *Note here that the minus sign is used to take care of the Coriolis force direction based on flow direction.*) From this it is clear that when a pipe (with flowing fluid inside the pipe) is rotated at a constant torque, then, due to fluid flow in the pipe, Coriolis force will be generated. Then, based on the direction of fluid flow, this Coriolis force will produce either a braking torque or an accelerating torque. Also, as the mass flow changes, rotational deceleration/acceleration will change, i.e., the braking torque or accelerating torque will be proportional to the mass flow.

2. **Coriolis effect on vibration application:** As in a rotational system, in an oscillating/vibration system also Coriolis force is generated when there is fluid flow inside a pipe and the pipe is forced to vibrate/oscillate. On account of this Coriolis force, the mass of flowing fluid will move away from or towards the axis of vibration/oscillation. Again let us take a straight pipe filled with fluid (not flowing initially). Let an external force F_e be applied on the same to excite the pipe to vibrate. The excitation frequency is kept at the natural frequency of the tube to minimize the energy required for creating vibration. The driver shown in the middle sets the tube into oscillation at a natural frequency. With reference to the top part of Fig. VI/2.0.0-1B, when there is no flow (i.e., flow velocity $v = 0$), the tube will vibrate as shown in the top part of Fig. VI/2.0.0-1B, by the violet curve (i.e., a sinusoidal oscillation) in positive side oscillation by a continuous violet curve (and negative side oscillation by a dotted violet curve). In this curve it can be seen that at the midpoint, the external force F_{e2} is highest and in the two sides this is lower, meaning $F_{e1} < F_{e2}$. Let us first concentrate on the positive part of oscillation only for the time being. When flow starts from left to right, there will be acceleration of particles inside the pipe for flow from left to right, i.e., they will move from the lower force point to the higher force point of the external force. Naturally, such acceleration is in opposition to the mass inertial resistance and is felt as a force opposing the pipe's vibration. This is Coriolis force, and would oppose the vibrating force as shown. Therefore, at the inlet part there will be deceleration. In contrast, at the other part of positive oscillation, as we go from the middle to the outlet part, forces are lower than in the middle, so, by the same logic as discussed above (i.e., due to reducing force, opposing Coriolis force) there will be acceleration as shown. In a nutshell, from the front end up to middle there will be deceleration and from the middle to the other end there will be acceleration. On account of both these actions there will be slight distortion in the curve as shown by the blue dotted line in the lower part of Fig. VI/2.0.0-1B. If we now look at the other half of the oscillating curve (negative oscillation) shown on the right-hand part, exactly the opposite will happen, i.e., in the inlet section there will be acceleration (F_e and F_c in the same direction) and deceleration in the outlet section. This is shown by the red dotted curve in Fig. VI/2.0.0-1B (lower figure). It can be seen that there will be a driver (as in the middle) to initiate the vibration in the flow tube. On account of flow, there will be a distortion in the vibrating tube and the tube will decelerate and accelerate alternately, both at the inlet and outlet sections, i.e., when the inlet section decelerates the outlet section will accelerate and vice versa. Such distortion will be sensed by the sensors shown.

3. **Application of vibration in Coriolis meter:** In a Coriolis flow meter the phenomenon described above is utilized, and for this the various figures shown in Fig. VI/2.0.0-1C may be referenced. In this case, in place of a single tube, two tubes (as *normally* seen in Coriolis meter) have been considered. As shown in the top two figures of Fig. VI/2.0.0-1C, the driver will create a vibration in a straight tube filled with fluid (with $v = 0$, i.e., no flow). On account of this vibration, tubes will move outwardly and inwardly in an alternate manner as shown. When there is flow, the inlet and outlet parts of the tube will also move in opposition, inwardly and outwardly in an alternate manner, giving a distortion in the tube movement as shown in the bottom two figures of Fig. VI/2.0.0-1C. A detailed explanation for such movement has already been given in the above subsection. The movement of two sets of tubes is monitored by the two sensors. In this case two tubes have been utilized for better sensitivity. Thus, on account of the tube distortions, there will be a phase shift between the two sensors and this phase shift or time difference is proportional to the mass flow rate.
4. **Coriolis force:** From the discussions in Subsection 2.1.1.1, it can be seen that for any mass to reach from r_1 to r_2 in a rotational frame of reference, some additional energy is necessary. This may be pumping energy to push fluid through the tube. The inertia force which opposes the change is the Coriolis force, F_c. The *general expression* for Coriolis force is given by

$$\overline{F_c} = (-)2 \cdot m \cdot \overline{v} \times \overline{\omega} \qquad \text{(VI/2.1.1-1)}$$

where v is the velocity at which the mass moves from r_1 to r_2; and ω is the angular velocity of the rotating system. It is important to note that the negative sign is shown here to indicate that the Coriolis force is opposing the change.

2.1.2 THEORY OF OPERATION OF CORIOLIS FLOW MASS FLOW METER

Coriolis meters directly infer the fluid mass flow rate by measuring the Coriolis force on a vibrating tube(s). To be more specific, one would argue that Coriolis meters involving (normally two) tube(s), directly infer the mass flow rate of fluid in a pipe by sensing the phase difference in signal between the two tubes caused by Coriolis force. A Coriolis meter consists of one or more tubes. Though there are single-tube designs, mostly two-tube designs are used. The basic theory of operation of Coriolis principle (as already seen in previous section), involves the introduction of a rotating frame of reference into the flow tubes through which fluid flows. The vibration is not a completely circular rotation, yet it provides the rotating frame to give rise to the Coriolis effect [3]. These tubes are subjected to vibration at their resonant frequency by a drive coil. The oscillation is in proportion to the sinusoidal vibration. There are sensors located on the inlet and outlet sections of the tube(s). At no flow condition the two tubes are in phase. When there is flow in the tube, as explained in previous section, Coriolis force comes into action, causing twists in the tube from the inlet section to the outlet section, i.e., there will be very small meter tube distortions. Such twists or distortions are measured by critically located sensors. The twists/distortions would result in a phase shift between the signals generated by the sensors. The phase shift or difference in time is directly proportional to the mass flow rate. This is depicted in Fig. VI/2.1.2-1A.

From the above discussions it is clear that the measuring principle is independent of fluid properties such as density, temperature, viscosity, pressure, and conductivity. Coriolis meters have their own calibration factor which is independent of fluid properties but dependent on the geometrical design and materials of construction of the meter. It is worth noting here that in a Coriolis mass flow meter, the oscillation is kept at the natural frequency of the system. When there is a

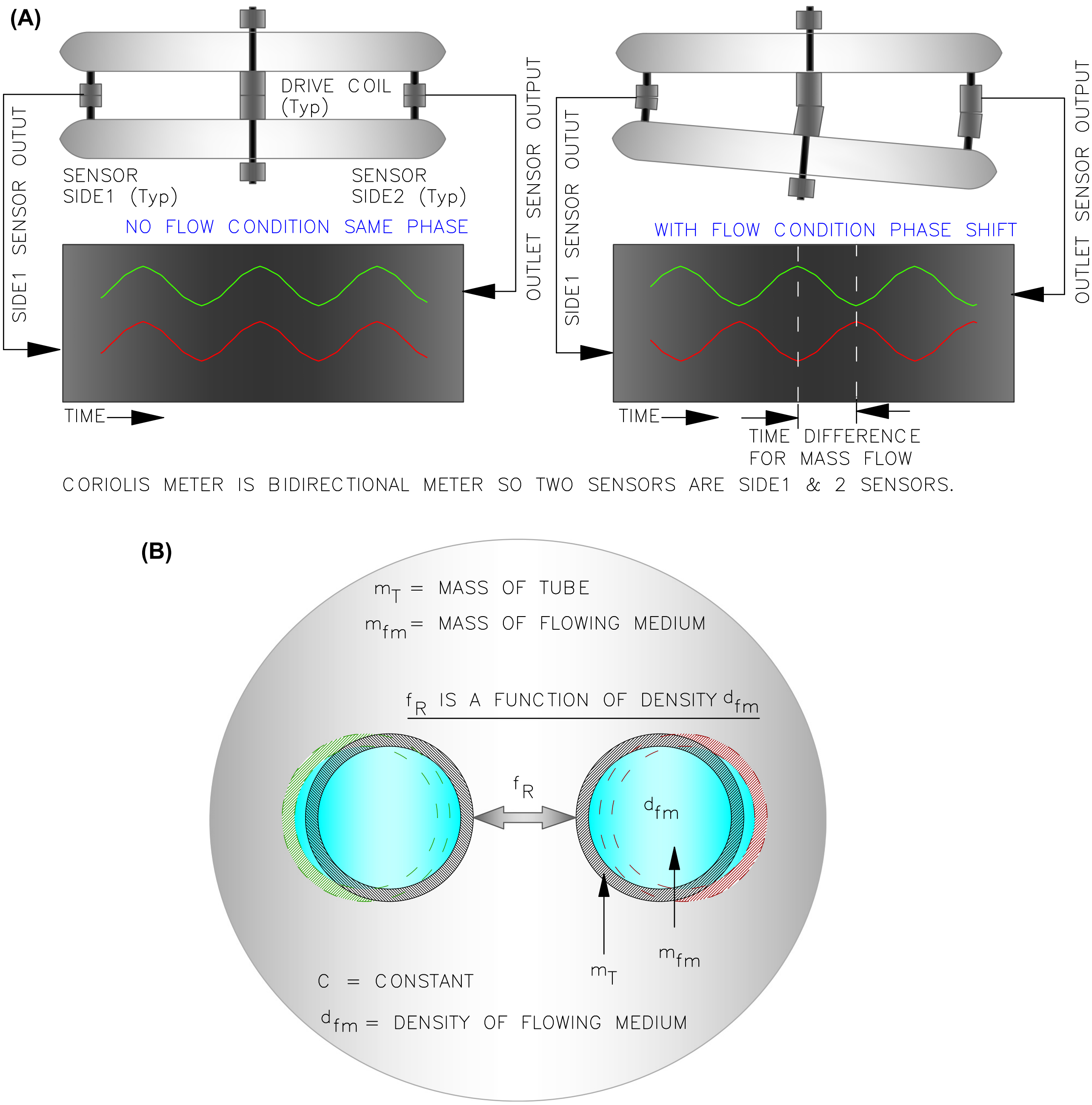

FIGURE VI/2.1.2-1 Coriolis meter operation. (A) Flow measurement by Coriolis meter. (B) Density measurement by Coriolis meter. *Idea from ABB; Courtesy of ABB.*

change in the mass, then there will be a change in the natural frequency. The volume inside the meter is fixed (if no appreciable change in temperature to cause meter size to change), by monitoring the frequency of oscillation density of flowing fluid can be measured. Therefore, any change in frequency of oscillation indicates that there is a change in the density of the fluid in the tube. If there is an increase in the natural frequency this indicates that there is a decrease in the density of the flowing fluid, and vice versa. In this connection, Fig. VI/2.1.2-1B may be referenced. If f_R is the resonant frequency, then f_R is a function $f(d_{fm})$. If m_T and m_{fm} are the mass of the

tube and flowing medium, then the density of the flowing medium is given by:

$$f_R = \frac{1}{2\pi} \cdot \sqrt{\frac{C}{(m_T + m_{fm})}} \qquad \text{(VI/2.1.2-1)}$$

$$d_{fm} = \frac{m_{fm}}{v} \qquad \text{(VI/2.1.2-2)}$$

However, "for gas applications, the 'flowing' or 'live' density measured by the Coriolis meter is not used for gas measurement, as its potential error in relation to gas densities is not acceptable for gas flow measurement purposes. Although this is the case, density measurement in gas applications can be used as an indicator of change in a Coriolis meter's flow factor and/or clean versus dirty" [4].

2.1.3 DESCRIPTIVE DETAILS OF CORIOLIS METER AND DESIGN ISSUES

The simplest arrangements with two parallel tubes have been detailed in Fig. I/3.1.4-1

1. **Components:** Depending on the design, the major parts of a Coriolis flow meter shall include but are not limited to the following:
   - Flow meter body;
   - Process connection flange;
   - Flow splitter;
   - Flow tube(s), with shape and quantity depending on design;
   - Casing enclosing flow tube(s);
   - Drive coil and magnet;
   - Set of sensors (pick off coil);
   - Compact electronics/transmitter;
   - Remote display;
   - Wall-mounted electronics;
   - Temperature sensor.

     Most modern Coriolis meters have a temperature-sensing probe built into the meter for sensing the process temperature. Such temperature measurements are useful to compensate for temperature-related mechanical effects such as tube expansion and/or changes in tube geometry. This also enhances the meter stability.

2. **Twin-tube versions:** The vast majority of commercial Coriolis flow meters available in the market are of twin-tube design with a flow splitter. The overwhelming majority of Coriolis instruments today are based on the twin-tube principle with a flow splitter and two bent meter tubes. The beauty of the twin-tube design is absolute symmetry of the two tubes which are unaffected by process parameters, such as density, temperature, viscosity, etc. Twin-tube design offers much improved performance, because of its ability to decouple the measurement system from the process environment, especially decoupling of the meter pipe vibrations from external vibrations, as the two identical tubes vibrate in counter-phase. One possible disadvantage of the twin-tube design could be in the flowing medium, which is prone to plugging. Such a flowing medium can plug the flow splitter, such as those found in food industries [1]. The temperature stability in the twin-tube version is also better [5]. The measuring principle, as we had seen in Section 2.1.1, requires vibration for determination of the phase difference. Such vibration is applied only on the tubes and is not related to the meter housing. Therefore, vibration has no effect on process flange/housing or on measurement. The sensors are identically mounted on the tubes requiring any additional support. On account of such a configuration it offers maximum suppression as well as a common mode of rejection of external influences like external vibration. While the sensors are mounted on the side tube (of the twin tubes), the driver coil and magnet sets are placed on the middle part of the two tubes so that there is mass balance and no excess free end is left. A properly designed system requires minimum energy to start the measurement, and should be able to measure very low changes in flow rate. It is preferred that the flow splitter should split the flow symmetrically between the two tubes. However, this is not an essential requirement. Actually, sensors measure the

displacements at two ends, so even if distribution in two tubes is not the same, displacement will not change and hence no additional errors will occur. Thus, it is noted that measurement is independent of the exact flow distribution. Therefore, it could be argued that a well-defined flow profile is not a requirement for a Coriolis meter and hence there is no straight length requirement to avoid flow turbulence due to any restrictions. Very high accuracy of measurement coupled with insensitivity to external influences make the twin-tube design the most popular Coriolis flow meter design.

3. **Single-tube version:** A typical single-tube design of a Coriolis flow meter has been shown in the top left part of Fig. VI/2.1.3-1. There are basically two designs involved, i.e., series loop and straight tube.
   - *Series design:* In order to eliminate the external vibration effect, the meter tube is bent into loops. In this type of design the advantage of the twin tube is that it eliminates the external vibration effect at the same time as there being no flow splitter, hence the chance of chocking is avoided and the size is kept smaller. In this type of design, the amplitude of vibrations and hence the phase shift, are measured between the tube loops independent of housing. However, as the length in series mode is greater, pressure drop will be higher and the accuracy level is low. Also, in this design it is not easy to clean the tube. The other single tube design is the straight tube design.
   - *Straight single tube:* The straight single-pipe design has advantages in that it can be more easily cleaned and has a reduced pressure drop. Also it is less harsh on the measuring medium [5]. In the straight tube, for vibration measurement, the difference is measured relative to the housing which, if subject to external vibration, measurement accuracy maintenance is very difficult. Also, the signal level is very small. Moreover, as the measured signals are appreciably smaller the accuracy level is poor. It is not easy to start and maintain resonance in a single straight tube design. "*Single straight tubes must be constructed thin and are available only for limited nominal diameters. For abrasive or corrosive measuring media, however, the thin wall sections of the meter tube can add additional safety concerns*" [5].
4. **Geometrical shapes:** The tube design in a Coriolis meter is the most critical aspect in meter design. Major points to be addressed include but are not limited to the following:
   - Flow sensitivity;
   - Pressure loss;
   - Material selection;
   - Tube size;
   - Tube thickness;
   - Frequency of operation;
   - Thermal expansion.

   Short discussions on various geometrical designs and how such designs affect the aforesaid factors are covered here. There are a number of designs for flow tubes for Coriolis flow meters. The main aim of all the design variations is to amplify the effect of the Coriolis force by the geometrical form of the tubes. From the concept of Coriolis force discussed in Section 2.1.1 it is clear that the *larger the Coriolis effect* becomes, the larger the time or phase difference between the flow sensors becomes, so it is easier to sense the flow. From Eq. VI/2.1.1-1 one can get that it is possible to increase the Coriolis force by changing ω.
   - *Larger loop:* In order to get greater Coriolis force it is often seen that larger loops are deployed. However, larger loops call for more space. Also, with larger loops external disturbances are enhanced. So, as this does not contribute anything to increase the zero stability of the meter, the signal-to-noise ratio does not change significantly. A larger loop would increase pressure loss. Also, a larger loop means higher mass, and hence lower resonance frequency.

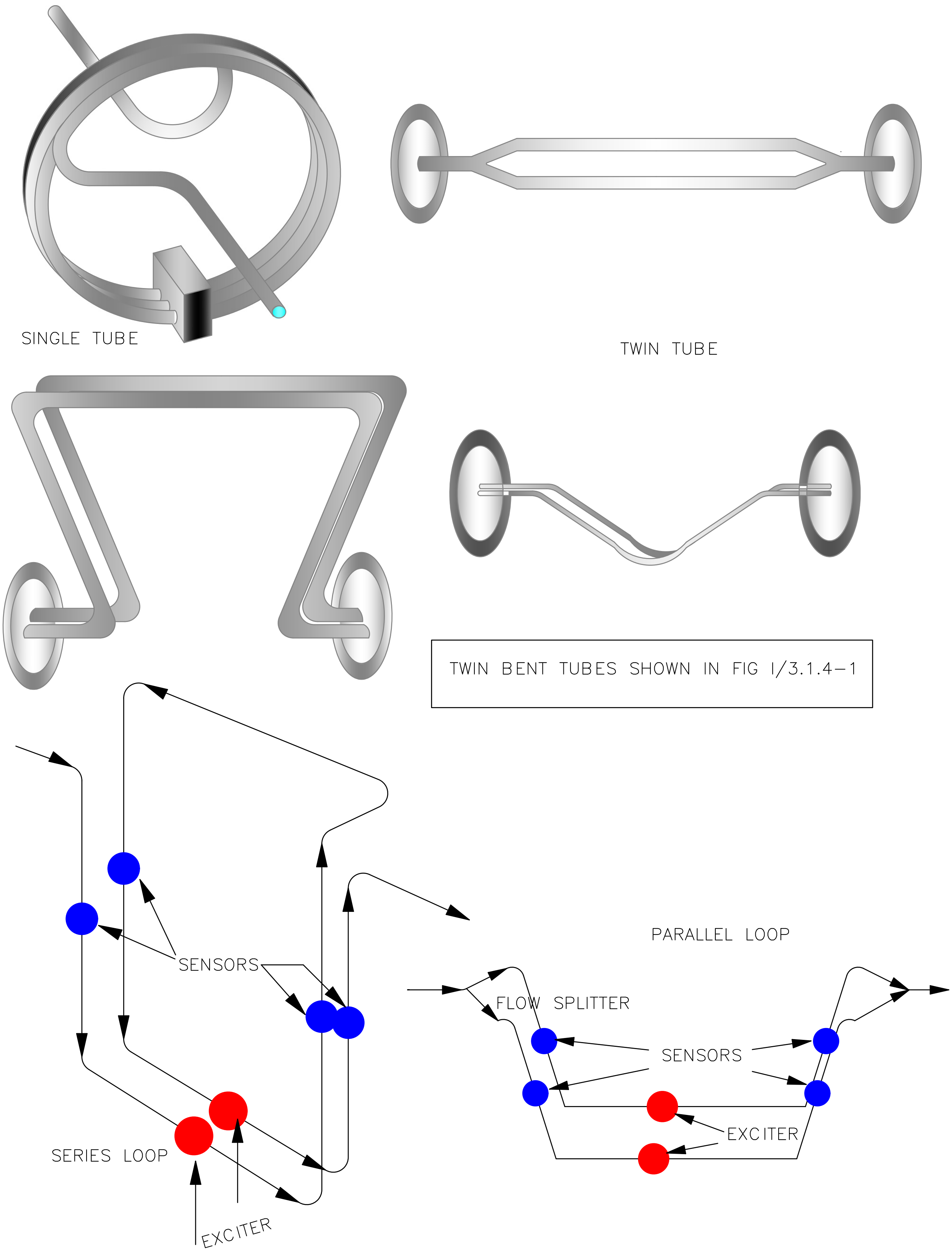

FIGURE VI/2.1.3-1 Geometrical shape of Coriolis meter. *Courtesy of ABB.*

Normally, external influencing vibrations are at a lower frequency. Therefore, if the systems operate at higher frequency, then the lower-frequency effect will be felt less. With efficient modern electronics such a need for force enhancement is not felt. Therefore, in modern meters there is no need to increase the loop, rather lower pressure loss is the aim. Hence, a compact design should be opted for, which will have a lower pressure drop with at the same time the external influence from vibration being less. With advanced electronics, the requirement for a larger Coriolis force is also managed.

- *Two curved tubes:* Coriolis meters with two curve tubes (as shown in the top left part of Fig. I/3.1.4-1), provide the greatest sensitivity to flow and offer a high turndown ratio. Flow sensitivity in a Coriolis meter is defined as the time difference (phase shift) per unit mass flow. Thermal expansion is another major contributing factor for selecting the twin bent tube design. It is likely that there will be variations in process temperature. However, the changes in the metal temperature of the meter supports may not be too high as part of the heat will be dissipated through convection and radiation. This will obviously create large temperature differences between the measuring tube and housing, which would cause an increase in the axial forces of the tube. In the case of a straight tube such a force will be very high and for a bent tube design this will be much lower. It also depends on the expansion coefficient of the tube material. Normally used tube materials such as stainless steel have a high expansion coefficient and these materials are not suitable for straight tube design; in such cases a twin bent tube is a good option. However, the twin bent tube meter design and production process are very critical because the symmetry of the two tubes is an absolute necessity.
- *Straight tube design:* As materials like titanium or zirconium offer a small temperature expansion coefficient, the majority of commercially available Coriolis meters with straight tubes use these materials for the measuring tubes [1]. Usually straight tube designs have restricted application in processes with the maximum temperature normally below 200°C.

5. **Fluid loop:** From the above discussions it is clear that there are two kinds of fluid loops. One is a series loop as applicable in single-tube design. In this loop the path length is too large, and hence pressure loss is greater. Therefore, the larger tube diameter is necessary to reduce the pressure loss. However, in that case there will be greater rigidity but less sensitivity to the Coriolis force at low flow conditions [6]. A parallel loop is applicable for twin-tube design (e.g., twin-tube bent design). In this loop, on account of the flow splitter and recombination, there will be greater pressure loss [6]. Also, on account of the flow splitter, there will be the possibility of clogging in some applications. Fluid loop paths have been shown in Fig. VI/2.1.3-1 (lower part).
6. **Driver for vibration:** Basically, the driving system is used to generate the vibration in the flow tube. In a twin-tube design, a drive coil is mounted at the center of the two flow tubes to vibrate the process fluid and tubes at a natural harmonic frequency, i.e., at resonance. Meter electronics applies a sinusoidal current to the drive coil to maintain the resonance at a specific amplitude. On account of the sinusoidal signal the magnet is attracted and repelled to create vibration in the two coils.
7. **Flow and density sensor:** Two sets of sensors are located at two flow tubes, one in each side of the inlet and outlet. Each set at inlet/outlet consists of a magnet and a pickoff coil. As the tubes vibrate the coil moves through the magnetic field and generates a sine wave proportional to that motion. Therefore, pickoff coils in conjunction with the magnets produce

a voltage in response to the resonance motion. These signals are taken to the electronics of the meter. In the electronics of the meter, these responses of the pickoff coils undergo Digital signal processing (DSP) for estimation of phase difference, i.e., the time difference between the two coils at the inlet and outlet sections to calculate the mass flow based on the Coriolis principles as already discussed. Similarly, from the response of the pickoff/sensors electronics the frequency of vibration for density measurement is estimated. Apart from the magnet and coil type sensor, it has been found from the literature that capacitive sensors are also used. However, the author has not experienced this in commercial meters.

8. **Temperature sensor:** It is known that mechanical properties change with temperature. Therefore, with a change in process/ambient temperature the properties of flow tubes also change. Such a change may lead to axial stress as well as a shift in Young's modulus. With an increase in temperature faced by the tube its stiffness will decrease and Young's modulus will be lowered. It goes without saying that it will affect the flow and density readings. In order to compensate for such influences in the reading, a temperature sensor—resistance temperature detector (RTD)—is normally included in Coriolis flow meters. Furthermore, because a temperature difference between the measuring tube and the housing results in an axial force, a second temperature sensor is needed to adjust the reading of the flow meter [1]. Since Coriolis meters include temperatures probe(s), they can be used as a third parameter reading from the meter.
9. **Electronics:** The electronic circuit associated with a Coriolis meter is a feedback control system with digital communication self-diagnostics. If one looks at the different functions one can divide the system functionally into the following subfunctions:
   - *Driving functions:* This circuit is responsible for initiating tube oscillations at specified amplitude and a given resonant frequency. Without a feedback control system this is impossible. If suddenly the fluid property changes then it will affect the excitation, i.e., amplitude and/or frequency will change. Such changes could be seen in different ways, i.e., sudden appearance of entrapped gas bubbles or variation in fluid density. Therefore, through feedback control such changes need to be sensed and adjust the circuit accordingly to maintain the oscillation amplitude at the new condition of entrapped gas. If the fluid density changes it has to initiate oscillation at a new frequency so that the change in density can be measured.
   - *Sensing:* Like any other flow meter electronics, Coriolis meter electronics also needs to handle sensor signals from two sets of sensors, which are very small in amplitude. The signals have to be amplified before being sent for digital signal processing. In addition to this electronics needs to perform a comparison of the two signals to find the phase difference. Also it has to handle the fluctuations in the signals and perform the same function precisely so that no additional errors come into the system.
   - *Power supply:* In the system normal AC supply is accepted and an internal power supply is developed; the power supply could be a switching power supply.
   - *Computation unit:* The electronics also support a computation unit, e.g., from mass flow and density it can also provide volume flow. Apart from these there are a number of compensations (e.g., pressure effect compensation) that need to be accommodated in the electronic computation unit. A Coriolis meter in multivariable measurement and computation has been depicted in Fig. VI/2.1.3-2.
   - *Normal output:* The outputs can be in different forms, such as current output, pulse output, and or HART (protocol) output or fieldbus output signal, or digital link output in RS 485 in (MODBUS).

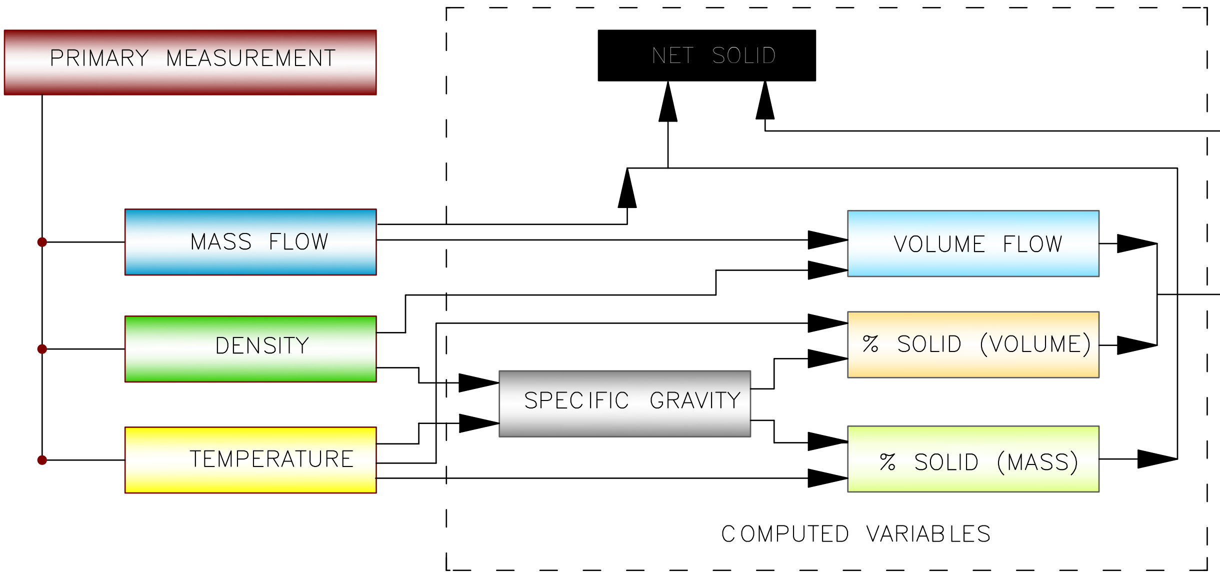

FIGURE VI/2.1.3-2 Coriolis multivariable meter.

- *Auxiliary input/output:* The majority of meters also handle auxiliary input/output, such as status input may be in different forms such as fieldbus or digital links like RS 485 (MODBUS). Similarly, there could be an alarm output which could be potential free contact or open collector output. There could also be status output.
- *Operator interface:* Within the operator interface there are two different sections: the display unit and operation keys. Most of these meters have back-lit LCD/LED displays of specified numbers of lines containing specified numbers of characters to display not only local output but also many other technical data for carrying out various functions (start up)/programming, etc. These are normally preprogrammed optical switch, for example. All systems have their own programs and software to support these technical issues.
- *Additional functions:* There are a number of additional functions electronics needs to perform, such as galvanic isolation, switching, load matching, etc.
- *Digital communication:* The HART protocol supports direct configuring of the meter with a high baud rate. Most of the meters are sufficiently intelligent to support fieldbus communication, e.g., Foundation fieldbus/Profibus also. These are detailed in Appendix VII. As the meters need to operate in hazardous areas they require the necessary certificates from the appropriate authorities. They also support safe fieldbus for which Ref. [7] may be referred to.
- *Mounting:* Electronics may be mounted integral with the meter as a compact flow meter (i.e., sensing and transmissions as one unit) or the electronics could be remote. Remote electronics could be connected to the preamplifier by cables. These have been detailed in Fig. VI/2.5.0-1B.

The meter description is now concluded and we now look at the meter characteristics.

2.1.4 CORIOLIS METER CHARACTERISTICS

The following are the major characteristics of the Coriolis meter:

1. **Process parameter effect:** Mass flow measurement and accuracy of measurement are independent of process fluid conditions such as pressure, temperature, composition, viscosity, etc. However, the pressure drop/loss in the tube not only depends on the fluid loop

discussed above but is also dependent on operating conditions and the composition of the flowing medium.

2. **Recalibration:** Recalibration of the flow meter is not necessary in most cases.
3. **Decoupling and balancing:** The Coriolis measurement principle involves the generation of vibration in the measurement system. The meter must be decoupled from any environmental or external disturbances, otherwise pipe vibrations, etc. could jeopardize the measurement. This is normally done with the meter design by use of twin identical flow tubes already discussed above. Also, it is necessary to ensure that the vibration of the meter in any case is transmitted to other parts of the body. Therefore, balancing of the meter is an absolute necessity.
4. **Tube design variations:** There is a wide range of tube design variations available for the Coriolis meter, including tube geometry, number of tubes, etc. These have been discussed at length in Section 2.1.3 above—and no are not repeated here.
5. **Electromagnetic signal decoupling:** The amplitude of oscillation in a Coriolis meter is in the range of 100 μm [1], therefore it is clear that a very small excitation current is applied. It is necessary to ensure that the general electromagnetic compatibility (EMC) requirements, as per the applicable standard/guidelines, are maintained.
6. **Zero stability:** Zero stability is an important factor for Coriolis meters. On account of construction of the flow/sensing tube(s), each Coriolis sensor will show a very small offset signal, even when true mass flow is zero. This is called the zero stability (error) and is specified for accuracy separately for all Coriolis instruments. The zero stability for each model and size is different. The zero stability error for each meter model is a fixed value. Therefore, zero stability has a greater effect on performance at lower flow rates when performance is expressed as a percentage of the actual flow rate. Thus, when the flow approaches the lower end of the flow range the accuracy deviates from the claimed/stated accuracy. Zero stability is also a function of the turndown ratio for the meter. Therefore, one may think of zero stability as how well the zero of the meter can be calibrated. Normally one can relate zero stability and accuracy by the relationship: ***accuracy* = *(zero stability/flow rate)* × *100.*** The zero stability effect is more prominent with a turndown ratio > 20:1. Naturally, the accuracy value falls with a higher turndown ratio. In order to get some idea of the value of zero stability some typical data could be: meter size DN50; maximum flow: 70,000 kg/h; zero stability error value: 3.5 kg/h, i.e., typically *0.005% FSD*. For this it is better to use data from a reputed manufacturer, as given in Table VI/2.1.4-1, to see how the accuracy and pressure loss are related.

   Repeatability is affected by zero stability. Here an interesting fact is that the higher the flow the greater will be the pressure loss, but it will be more accurate. However, with higher turndown at lower flow, pressure loss will be less but at the same time accuracy will also be less, i.e., for a high turndown ratio the accuracy will suffer. This has been depicted in Table VI/2.1.4-1.

TABLE VI/2.1.4-1 Relationship Amongst Accuracy Turndown and Pressure Loss [3]

Turndown	60:1	20:1	10:1	2:1	1:1
Accuracy % AR	±0.25	±0.05	±0.05	±0.05	±0.05
Pressure loss	0.0006 barg	0.004 barg	0.015 barg	0.28 barg	1.0 barg

Courtesy of Micro motion Emerson process management.

7. **Zeroing:** At the starting of operation, meter zeroing of the Coriolis meter is necessary. Apart from this, if there are significant changes in process and/or ambient conditions it is better to carry out a process to get rid of the zero offset. Zero adjustments shall be carried out with the flow tube completely filled but with zero flow. During zero adjustments there should not be any entrapped gas/solids.
8. **Changes in fluid:** The same meter can be used for different fluid types without recalibration. It can also be used with mixed fluids, such as liquid with entrapped gas/solids, but accuracy may suffer. Some meters available can be used for two-phase fluids, e.g., Elite class Coriolis meter of Micro motion (Emerson Process Management).
9. **Pressure drop in gas application:** It is important to note that the pressure drop through the sensor depends highly on operating pressure, temperature, and gas composition. It is therefore recommended that for sizing the meter for gas applications this is done individually, utilizing a suitable software tool from the manufacturer.

2.1.5 OPERATING AND ENVIRONMENTAL CONDITIONS

It is needless to mention that the operating and environmental conditions of Coriolis meters varies greatly with the type and design of the Coriolis meter, i.e., there may be variations with model numbers. However, the data presented here are typical ones (maximum value) normally specified by the manufacturers. For each application the reader is advised to consult the manufacturer. Also, there will be changes to the operating conditions for meters meant for liquids and gases.

1. **Operating process pressure:** Depending on the size and application, process pressure varies from as low as 10 to high 190 barg, e.g. RCS 005 of Badger meter. This is mainly applicable for standard stainless steel models. Models with alloys and for high-pressure models the pressure could be >400 barg. These are mainly flow tube ratings, case pressure ratings could be *lower*.
2. **Flange pressure ratings:** Flanges are available in international standards. Typical available ratings are PN 16−100 in DIN standard, i.e., ANSI rating of 150−600 lb (JIS 10−43K). For high-temperature versions the pressure rating may be lower.
3. **Process temperature:** −50 to 400°C (there could be restriction of ambient temperature below 50°C). Here restrictions come from two major issues: seal materials and electronics. Ambient temperature also has an influence. When remote electronics are used it is possible to withstand more harsh environmental temperatures than those for integral electronics. The highest temperature value given here is for the high-temperature version; normal versions may have a highest temperature of around 200°C. Wherever seal is used, restrictions may come from the seal materials as listed below for some typical materials [8].
   - *Viton:* −15 to 200°C;
   - *EPDM:* −40 to 160°C;
   - *Silikone:* −60 to 200°C;
   - *Kalrez:* −20 to 270°C.
4. **Flow range:** Size and flow range are listed separately below (2.1.6.1).
5. **Pressure loss:** This is listed below separately.
6. **Ambient temperature:** −40 to 70°C (e.g., FCB400 of ABB) for all versions. However, for remote electronics lower temperatures may be achievable, e.g. −100°C.
7. **Storage temperature:** normally −40 to 80°C.
8. **Humidity:** up to 95% noncondensing.
9. **Shock resistance:** IEC 68-2-31.
10. **Vibration:** IEC 68.2.6 up to 1g; 5−2 KHz.
11. **EMC:** directive 89/336/EEC per EN 61326.
12. **Enclosure:** IP 65/66 NEAM4X for electronics.

2.1.6 SIZE AND FLOW RANGE

To get an idea of the flow in a Coriolis meter in liquid and gas applications refer to Table VI/2.1.6-1. During the discussions on zero stability it is clear that at the lower end the flow zero stability is very important and it directly affects meter accuracy. Therefore, the minimum flow of the meter range is dictated by the *minimum acceptable accuracy at minimum flow*. Again, from Table VI/2.1.4-1, one can see that with an increase in flow the pressure drop increases. Therefore, *allowable pressure loss at maximum flow decides the maximum flow* of the meter range. However, a few guidelines/recommendations given below may be followed.

1. **Liquid flow:** For flow from the flow range given, it is recommended to select the fluid range based on the following recommendations. Liquid flow: should be within 5%–100% of the range for corresponding meter size, and any flow <1% should always be avoided.

TABLE VI/2.1.6-1 Meter Size and Flow Range (Liquid—for Gas Follow Guideline Above) (Reputed Manufacturer's Data)

Meter Size (mm)	Meter (Inches)	Flow Range (kg/h)	Flow Range (lb/h)
8	3/4	0–2000	0–4410
15	½	0–8000	0–17,637
25	1	0–35,000	0–77,162
40	1½	0–45,000	0–99,000
50	2	0–90,000	0–198,416
100	4	0–520,000	0–1,146,404
150	6	0–860,000	0–1,895,975
250	10	0–220,000	0–4,850,400

2. **Gas flow:** The gas flow range is dependent on gas density at operating conditions, therefore this may be obtained from the liquid flow range. The following is a general guideline

$$(FR)_{gl} = (FR)_{ll} \times \rho_{gop} \times MF$$

where $(FR)_{gl}$ = gas flow range for a line size; $(FR)_{ll}$ = liquid flow range for same line size; ρ_{gop} = gas density at operating condition; MF = meter factor for particular model number for a particular line size recommended by the manufacturer. Let us take an example:

Let the flow range in a liquid be 90,000 kg/h for DN 50; gas density at operating condition (20°C at 50 kg/cm^2) is 60.3 kg/m^3 and the meter factor for DN50 for a particular model is 90.

Then the gas flow range will be 90,000×60.3/90 = 60,300 kg/h.

The flow velocity of gases in the meter tube should be < approximately 100 m/s (328 ft/s), 0.3 mach, and velocity above 80 m/s may lead to increased reproducibility [9].

2.1.7 PRESSURE LOSS

From the discussions in Section 2.1.3 it is clear that pressure loss in various tube designs will be different. Also, pressure loss for series and parallel loops are different. Thus pressure loss is dependent not only on the internal diameter of the flow tube and medium viscosity, but is also dependent on tube design, geometry, and length of the tube. In the case of a twin-tube design the flow splitter plays an important role in deciding the pressure loss in the meter. Pressure loss as a function of turndown ratio has been elaborated in Fig. VI/2.1.4-1, i.e., the higher the flow the higher will be the pressure loss. Pressure loss in Coriolis flow meters is normally obtained from the curves provided by the manufacturer for particular sizes of meter. Pressure loss can also be obtained by the formula given below.

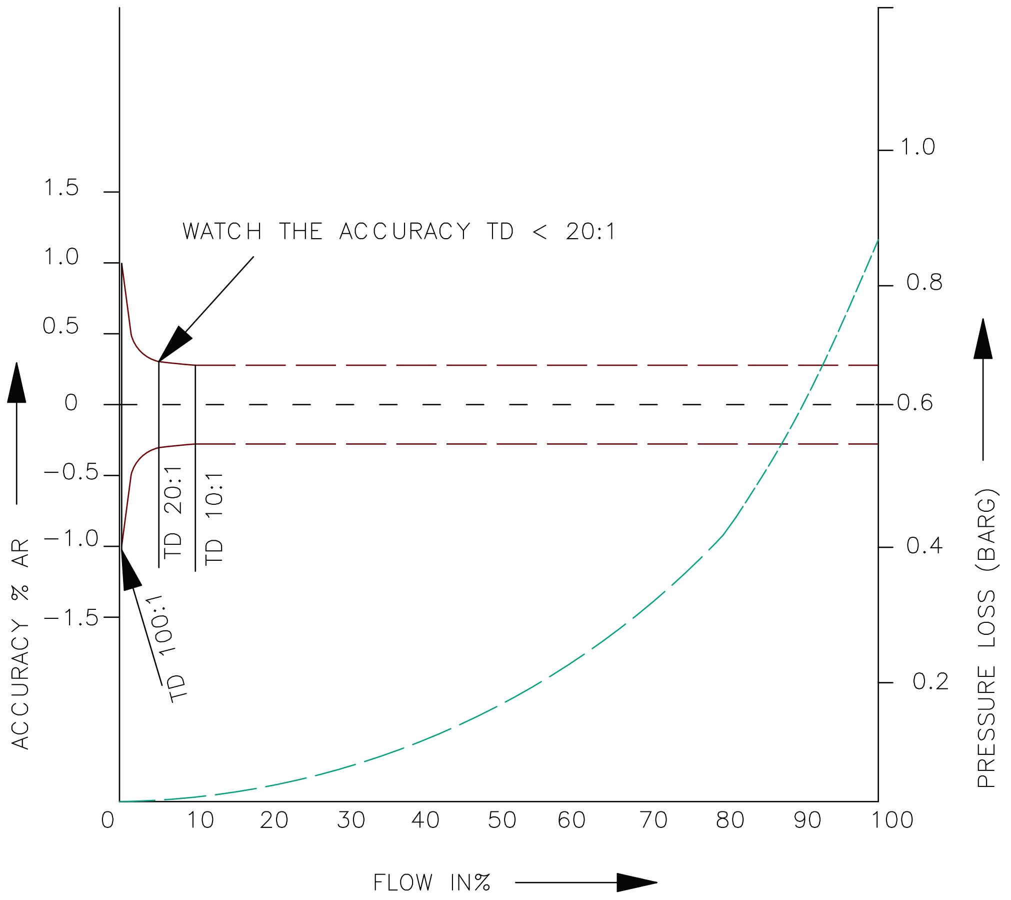

FIGURE VI/2.1.4-1 Accuracy and pressure loss for CMFM.

The Reynolds number can be obtained for mass flow by rearranging Eq. I/1.1.2.2-2:

$$R_e = \frac{4 \cdot \dot{m}}{\pi \cdot d \cdot v \cdot \rho} \qquad \text{(VI/2.1.7-1)}$$

$$\text{For} \quad R_e \geq 2300; \Delta p = k \cdot v \cdot^{0.25} \cdot (\dot{m})^{1.85} \cdot \rho^{-0.86} \qquad \text{(VI/2.1.7-2)}$$

$$\text{For} \quad R_e\ 2300; \Delta p = k_1 \cdot v \cdot \dot{m} + \left(K_2 \cdot v^{0.25} \cdot (\dot{m})^2\right)/\rho \qquad \text{(VI/2.1.7-3)}$$

Constants k, k_1, and k_2 depend on the flow meter size and meter type—specific data for an individual manufacturer model [8].

Typical pressure drop in various Coriolis flow meters has been indicated in Fig. VI/2.1.7-1. This pressure loss curve has been developed based on data from a reputed manufacturer.

Fig. VI/2.1.7-1 shows how the pressure loss varies with viscosity changes. It also shows that as viscosity increases the flow range is shortened.

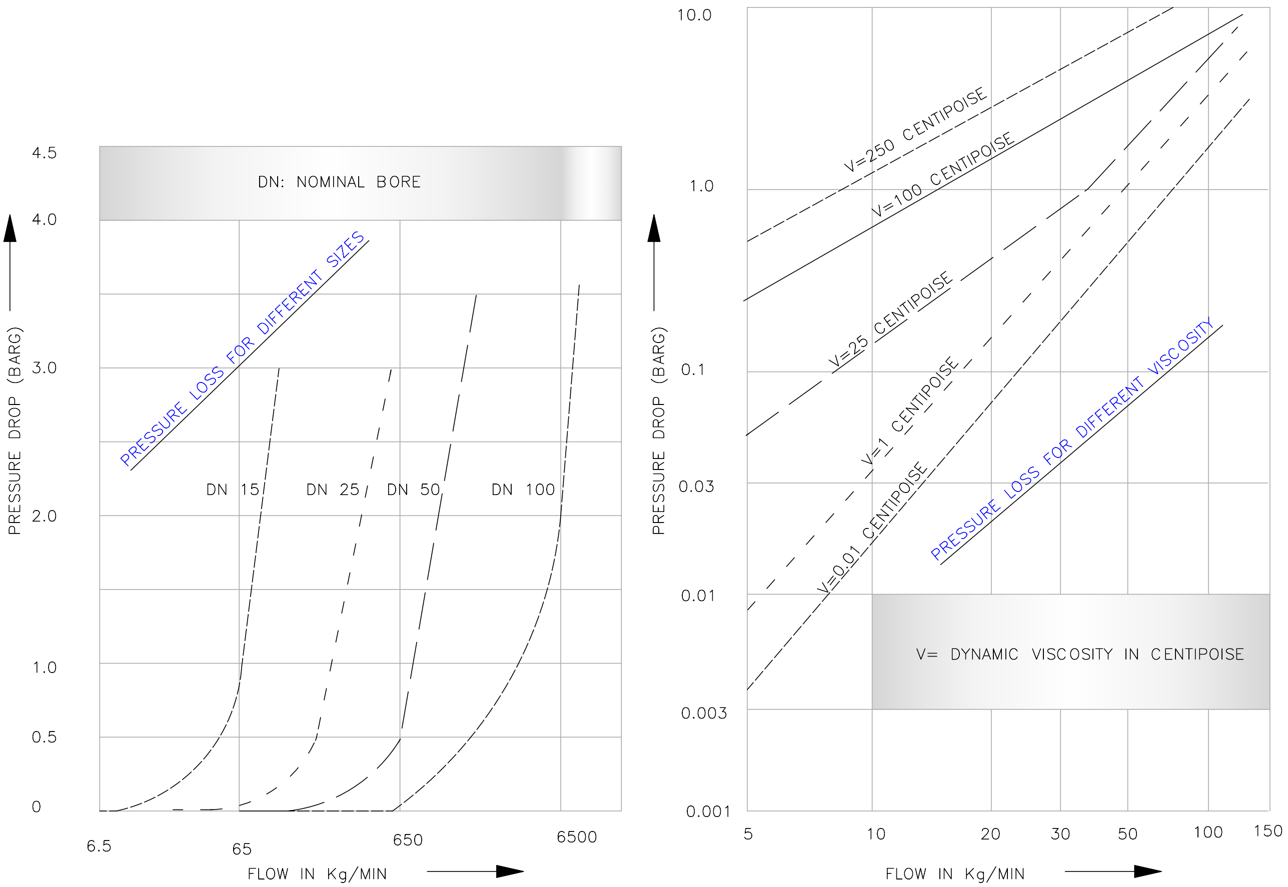

FIGURE VI/2.1.7-1 Pressure loss curve for CMFM. *Developed from Coriolis Master FCB330, FCB350, FCH330, FCH350 Coriolis Mass Flow Meter, Operating Instruction OI/FCB300/FCH300-EN Rev. F, ABB limited, May 2014. https://library.e.abb.com/public/d65feba9d7ab7fd7c1257cdd0046180e/OI_FCB300_FCH300_EN_F.pdf of ABB. Courtesy of ABB limited. Developed from Micro Motion Document; Courtesy of Emerson Process Management.*

2.1.8 MATERIALS OF CONSTRUCTION AND PROCESS CONNECTIONS

1. **Materials of construction (MOC):** Meters are available in a variety of materials. The major materials used are as follows:
   - *Wetted parts (general):* ANSI 316L (1.4404 or 1.4435) and nickel alloy C64 used in Coriolis meter. There could be other materials, such as titanium may be used in specific cases. Materials for different components popularly used include but are not limited to the following:
   - *Meter tube:* Stainless steel (1.4530/1.4404 316L)/Alloy C22 2.4602/N06022 (high-temperature version)/titanium of different grades;
   - *Seal (where applicable):* Refer to Subsection 2.1.5.3;
   - *Sensor housing:* Different grades of SS/nickel plating;
   - *Transmitter housing:* Powder coated die cast aluminum, SS different grades;
   - *Process flange:* SS 1.4404, 316, 316L, etc./Alloy C22 2.4602/N06022/grades of titanium. While using different flanges it is necessary to derate the same as per the curve provided for the flange. Whenever the flange rating for a flange type and material is specified, it has a maximum rating. Let us take an example to elaborate: One PN 100 flange of stainless steel DIN flange 1.4571/1.4404 has a pressure rating of 100 bar. This is true

up to a certain temperature (e.g., up to 50°C), however if it is to be used at a higher temperature than from the chart/graph, the pressure rating of the same can be obtained for that temperature, e.g., 200°C—it is close to 80 barg. Thus for specific flanges proper derating is to be carried out as per the curve provided by manufacturer for the flange. This has been elaborated in Chapter V.

2. **Process connection:** In most cases flanged process connections are used for Coriolis mass flow meters. However, in certain cases threaded connections are also seen. These are illustrated below. MOC of the flanges and their derating issue have already been discussed.
   - *Standards:* Flanges are available as per international standards, such as ASME (B16.5)/DIN (2501)/EN (1092)/JIS (B2220). These are only examples of popular flanges used.
   - *Size:* Based on meter size between nominal bore 8 −150 mm.
   - *Rating:* ANSI class 150−1500 lb or PN 16 to PN 160, for example.
   - Apart from flanges other process connections could be threaded pipe connection, as per DIN 11851, and Tri clamp, as per DIN 32676. However, these have limited use in terms of pressure (up to 40 bars) and temperature range (between −40 and 140°C).

2.1.9 PERFORMANCE DATA

The majority of Coriolis meters available in the market have quite good accuracy. The following are a few technical data based on which the performance of Coriolis mass flow meters is evaluated. Prior to obtaining performance details, reference conditions need to be established.

Reference condition: The performance capability of a Coriolis meter is determined under certain reference conditions. These reference conditions for various manufacturers may vary in some points and conditions. Each manufacturer specifies these details in their manual. Normally the reference conditions of various manufacturers vary widely.
Reference condition: Typical technical data for the reference condition;
Medium: water;
Temperature: 20−30°C;
Pressure: 2−4 barg;
Ambient temperature: 25°C;
Line voltage: Meter name plate rating;
Standard: Accredited calibration rig as per ISO 17025;
Zero point: operating condition;
Output calibration: Pulse (manufacturer standard);
Accuracy: Typical value as per Table VI/2.1.9-1;
Repeatability: Typical value as per Table VI/2.1.9-1;
Zero stability: Refer to Subsection 2.1.4.6.

We now look into the features and application areas of the meter.

TABLE VI/2.1.9-1 Performance Data for Coriolis Meter [3]

Performance Parameter	Liquid Measurement		Gas Measurement	
	Accuracy	Repeatability	Accuracy % AR	Repeatability % AR
Flow[a]	±0.1% AR	±0.05% AR	0.25% AR	0.2% AR
Density	±0.5 kg/m^3	±0.2 kg/m^3	Not applicable	
Temperature	±1°C + 0.5% AR	±0.2°C	±1°C + 0.5% AR	±0.2°C

[a] *Volume flow (from mass and density) with accuracy of 0.4% AR available for some manufacturers.*
Courtesy of Micro motion.

2.2.0 Features and Application Areas for Coriolis Mass Flow Meters

Amongst the various fluid flow meters, these have some special features not normally encountered in other flow meter types. In view of this, these flow meters find a good number and types of applications in process and other industrial plants.

2.2.1 FEATURES OF CORIOLIS METERS

In this section the advantages and limitations of Coriolis meters are discussed.

1. **Advantages:** The following are a few advantages of Coriolis meters:
   - Direct measurement of true mass flow without the need for a flow computer and the need for pressure and temperature compensation for density variations. It also directly measures the density of the flowing fluid.
   - The Coriolis meter directly gives multivariables, i.e., mass flow, density, and temperature, with a lower number of instruments to be specified and installed for any particular application.
   - With the availability of both mass flow and density in the same meter it is possible to compute volume flow also.
   - The Coriolis meter can be applied for measurement of mass flow for liquid, gas, slurry, and Newtonian and non-Newtonian fluids.
   - Mass flow measurement by Coriolis meters is independent of process parameters like pressure, temperature, conductivity, and viscosity.
   - The Coriolis meter can be used for any process fluid, irrespective of its density.
   - The Coriolis meter can measure both forward and reverse flow.
   - High-accuracy meters can provide an accuracy of 0.1% AR for liquid and 0.25% for gas—this may not be achievable with other meters.
   - The power requirement of these meters is low.
   - Modern meters are smart meters with digital processing and communication facilities, coupled with diagnostics for easy meter operation and maintenance.
   - The Coriolis meter can provide a high turndown ratio with moderate pressure drop and good accuracy.
   - With no moving parts, the maintenance requirement is low.
   - As flow profile changes do not affect the measurement, there is no straight length requirement for installation.
2. **Limitation:** The following are a few limitations of this meter:
   - Capital cost of the meter is the major constraint, and may not be justified for cases where the value of the fluid or criticality of measurement is not that important.
   - Coriolis meters are available only in limited sizes, the normal available maximum meter size is 250 mm but 400 mm is possible but uncommon.
   - Coriolis meters are less popular in gas flow applications on account of low density, especially for low-pressure services.
   - The probability of being affected by external parameters is discussed later.
   - Pressure drop is a major concern in many flow tube designs.
   - Although measurement is not affected by viscosity, high viscosity creates greater pressure loss which is of major concern.
   - Density measurement by Coriolis meters in gas applications is not accepted in many applications.

2.2.2 APPLICATION AREAS FOR CORIOLIS METERS

There are wide areas of application of Coriolis mass flow meters. They can be applied in practically any flow and density measurement, as long as cost is not a big constraint and that it is suitable for line size of the application. Similarly, Coriolis flow meters find their applications in almost all industrial sectors, such as power plants, oil and gas applications, chemical plants, food and

beverage industries, etc. The following are only a few examples where the meter is extensively used:

1. Oil and gas separation;
2. Onshore and offshore applications, e.g., rotating head to shale shaker flow;
3. Measurement of fuel consumption;
4. Boiler and utility station applications, especially for burner fuel consumption;
5. Industrial furnace applications;
6. Measurement of adhesive and glue application;
7. Coating and hardening applications;
8. Measurement of vegetable oils and fats;
9. Food and beverage applications: milk, honey flow, ice cream flow;
10. Ethylene plants;
11. Pulp and paper plants: stuff box chemical feed/gas and fuel, coating; black and red liquor;
12. Dyes, fragrances, vitamins, and other pharmaceutical applications;
13. Measurements of homogeneous suspensions;
14. Hydraulic fracturing;
15. Lube blending plant, oil–water emulsification;
16. Catalyst preparation and feed;
17. Various other concentration controls.

2.3.0 Influencing Factors Affecting Selection and Operation of Coriolis Meters

In this section short discussions will cover various influencing factors for meter selection and operation.

2.3.1 PRESSURE EFFECT

Whenever there is a change in operating line pressure, a bias in the flow tube may be noticed; the tube may become slightly deformed. This is often referred to as the "flow pressure effect." This is dependent on the materials chosen and the amount of change in line pressure. Such a "flow pressure effect" can affect the reading of the meter. High line pressure would put more resistance to the twisting force of the Coriolis effect, hence a given flow reading would be lower. Similarly, low line pressure would put less resistance to the twisting force of the Coriolis effect, so a given flow reading would be higher. Therefore, while selecting the meter necessary action may be planned to compensate for these effects. There are special designs to take care of this; in modern meters with digital signal processing (DSP), they are compensated in meter electronics based on the formula:

$$F_p = [1 + \{(P_e/100)(P_{st}/P_{cal})\}]^{-1} \quad \text{(VI/2.3.1-1)}$$

where F_p = pressure effect compensation factor for flow; P_e = pressure effect in %; P_{st} = operating static pressure; and P_{cal} = static pressure at which the meter is calibrated. Every Coriolis meter design and size has a different flow pressure effect specification and most Coriolis transmitters have provisions for applying an average flow pressure effect correction [4]. Often pressure transmitters are used to monitor static pressure for compensation.

2.3.2 TEMPERATURE EFFECT

Temperature has two effects on the meter. One is changing the mechanical properties of the tube and housing. As mentioned earlier in Subsection 2.1.3.8, this effect can be compensated for by direct measurement of temperature by RTD. In addition to this there will be a temperature effect on the zero offset and the performance of the electronics. Such an effect will be greater on compact designs than for remote electronic designs. Exactly for this reason meters with remote electronics will have a greater temperature-withstand capability. The drift in electronic components will usually lead to changes in the zero offset of the flow meter. However, such effects should be taken care of during the design and selection stage of the meter. For meter selections (especially for integral/compact versions) drift of electronics should be properly chosen for high-temperature applications.

2.3.3 RATE OF CHANGE OF FLOW

Flow surge often damages flow meters with moving parts. In the case of a Coriolis meter with an inlet flow splitter, the Coriolis meter blocks flow to the flow tubes and there is not enough inertial force to cause damage. With modern advanced designs it is possible to measure choke velocities, so any concern for rate-of-change in the meter is removed.

2.3.4 OVER-RANGE APPLICATIONS

Over-range, especially in gas flow measurement, is dangerous for most meters. In the case of over-range, especially for gas flow measurement, there may be a possibility of erosion due to high velocity. However, this possibility is not of much concern in the case of a Coriolis meter because most of the modern meters can support high velocity (for maximum velocity of a particular model the manufacturer may be consulted). In the case of CS material, it is possible that the tube first gets oxidized then eroded by gas velocity. However, as the meters in most of cases are made of stainless steel or nickel alloy this is not of much concern. In any case, if the gas has foreign materials, such as sand, welding rods, rocks, etc. it is possible that the meter may be damaged due to high velocity. In such cases it is recommended to use a *filter* to protect the meter.

2.3.5 FOREIGN MATERIALS AND MEDIUM QUALITY

Flowing medium quality deteriorates with ingress of foreign materials into the flowing medium. In the above discussions it has been recommended that filtration be used to get rid of foreign materials like sand, gravel, welding rods, etc. However, fine soft particles, such as iron oxide, oils, and dust may escape the filter and reach the meter. These may not damage the meter directly, but cause *build-up of debris*. Build up of debris can cause an imbalance in the flow tubes and out-of-specification shift in the meter's zero [4]. In the majority of gas flow applications as the velocity will be high these may be driven away. However, if there is a build up, then it will cause an error in readings at the lower end. In such cases, as a part of maintenance, zero checking is done and if this is beyond a tolerable range then it is better to recalibrate the meter so as to get the desired accuracy.

2.3.6 VIBRATION AND PULSATION

In modern meters the effect of vibration and flow pulsation has been minimized. Earlier there were also performance constraints from meter mounting. However, in modern meters manufacturers normally do not insert any mounting constraints. So, in this section short discussions will be presented on vibration and flow pulsation.

1. **Vibration:** As already stated, in modern meter designs the effects of external vibration from pumping systems and other vibrating devices have been minimized. Also, the frequency of such vibrations is much lower, and not near the resonant frequency (f_E) of the meter. Thus one can argue that error due to vibration effect on meter performance is below the acceptable error level and may be ignored.
2. **Pulsation:** Another issue of concern is pulsating flow, which often damages load-bearing gears in flow meters, such as PD meters/turbine meters. Generally, Coriolis meters are immune to fluid pulsations, except pulsations at the resonant frequency (f_E) of the meter's flow tubes and also at frequencies $f = f_C - f_E$, where f_C is the Coriolis frequency [1]. Therefore, if the meters have high working frequencies, then meters are much less sensitive to pulsation as well as external vibration. This is because both the resonant frequency and the difference are high. Also, in modern meters, it is possible to maintain accuracy even at fluid flow pulsations.

2.3.7 OTHER CONDITIONS

There are a few factors which may affect the performance of the meter, i.e., Reynolds numbers which have as such no effect on meter performance but meter sensitivity is affected near

laminar to eddy flow. We now analyze a few other conditions.

1. **Multi/two phases:** Meters are used for homogeneous two-phase flows, such as solid-liquid flow as in food processing plants [1]. However, meters in general cannot be applied for multiphase flow measurements. The following issues are important here: nonhomogeneous mixtures would result in fluctuating density, hence there would be a fluctuation in resonant frequency which would make the measurement out of gear. At higher levels of nonhomogeneity, there could be several problems, including the following:
   - A nonhomogeneous mixture would result in fluctuating density, and hence a fluctuation in resonant frequency, which would result in poor performance of the meter.
   - According to Coriolis principle, all particles of the medium are accelerated in accordance with the movement of the pipes. With high proportions of gas (or nonhomogeneous mixture), particles in the middle of the pipe will no longer complete the movement of the pipe. As result of this, the measured value will be systematically reduced [6].

   However, if the gas content is small and has homogeneous distribution, the mass flow measurement is not greatly affected.
2. **Low back pressure:** In the case of liquid measurement, if there is low back pressure then it may not be possible to ensure complete fill up of the meter. Naturally, in this situation, a stable vibrating condition cannot be ensured. Also, there lies the danger of cavitations if back pressure is low. This is because when the vapor pressure of the liquid at operating pressure is lower than the existing line pressure, there will be vaporization.

2.4.0 Specification of Coriolis Meter

After gathering some knowledge on the technical data of a Coriolis meter we now look at CMFM specifications. Table VI/2.4.0-1 gives the specifications for a Coriolis meter. *It is worth noting that the data given here are mainly based on data from reputed manufacturers. Also, effort has been made to put the best value or material for any specific criterion. Naturally, data given may not match with any specific manufacturer. Based on budget and application, readers should specify their requirements to get the optimum result.*

TABLE VI/2.4.0-1 Specification of Coriolis Meter

Sl. No.	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Liquid/gas limited two phase		
2	Design pressure	10–25 bar; 190 high-pressure version		
3	Design temperature	Normal −50 to 200°C high-temperature version 400°C		
4	Derating	Typical derating of flange as applicable. Typical example in Subsection 5.1.3.1 of Chapter V		
5	Environmental condition	Refer to Section 2.1.5. (point nos. 6 through 12 of section 2.1.5)		

Continued

TABLE VI/2.4.0-1 Specification of Coriolis Meter—cont'd

Sl. No.	Specifying Point	Standard/Available Data	User Spec.	Remarks
6	Pipe size and flow range	Meter for pipe size between 8 and 250 mm (nominal bore) are standard sizes available. Flow ranges are as per manufacturer's standard, typical one has been given in Table VI/2.1.6-1		
7	Sensing type	Magnet/coil (normal)		
8	Output	Pulse/4—20 mADC Smart version with HART protocol, fieldbus communication (e.g., PROFIBUS/ Foundation fieldbus) available		
9	Output function	Electronic totalizer, remote transmission, and other control function including filling/batch control, etc.		
10	Materials of construction	Refer to Subsection 2.1.8.1		
11	Enclosure class	NEMA 4X/IP 65/66		
12	Electronics unit	Powder-coated diecast aluminum, SS different grades		
Connection and Mounting Details				
13	Process connection and meter type	Flange as per ANSI/BS/DIN/JIS, etc.		
		Refer to Section 2.1.8 for details of flange and other type, i.e., threaded pipe connection and triclamp connections		
14	Electrical	½″NPT/ET ISO M20 or manufacturer standard		
15	Mounting	Horizontal/vertical/inclined (offshore)		
Performance and Other General Details				
16	Accuracy	Refer to Section 2.1.9 and Table VI/2.1.9-1		
17	Repeatability			
18	Zero stability	Important issue for CMFM. Refer to Subsection 2.1.4.6		
19	Certification	Necessary certification from appropriate authority for hazardous applications		
20	Applications	Liquid services only but could be used for almost all types of fluid be they corrosive/abrasive, only requirement minimum electrical conductivity to be maintained		

Continued

TABLE VI/2.4.0-1 Specification of Coriolis Meter—cont'd

Sl. No.	Specifying Point	Standard/Available Data	User Spec.	Remarks
21	Accessories	Meter support (as applicable), rate flow and totalizing indicator, transmitter, communication facility		
22	Hazardous applications	Possible with appropriate enclosure and suitable certification from competent authorities for transmitter also. Use of IS barrier		For hazardous application details refer to Ref. [7]
Transmitter Details				
23	Type	Remote/integral		
24	Response time	0%–90%: ~1 s		
25	Display	Mass flow/density/temperature/ volume flow		
26	Operator interface	Optical switch		
27	Power supply	230 VAC 50 Hz or 110 V 60 Hz with suitable adapter and converter		
28	Input/output	Admix of analog and digital input and output to accommodate pressure/temperature input, alarm output apart from meter normal output are common. Actual I/O depends on model and manufacturer. Also, USB port for configuration optional		
29	Feature	Forward and reverse flow monitoring, self-diagnostics		
30	Communication	Supports fieldbus communication. HART communication		
31	Special feature	If any to specify requirement		

2.5.0 Coriolis Mass Flow Meters Installation Discussions

Standard issues already discussed in connection with other meters previously are also applicable for CMFM and these include the following:

1. The measuring tubes should be full all the time for measurement;
2. Mixtures of gas and liquid, and/or entrapped gas/solid in liquid should be avoided;
3. For gas measurements, the tubes should be filled with gas only, otherwise suitable drainage could be utilized and suitable filters could be used to protect the meter;
4. Orientation and mounting location are as prescribed below;
5. Avoidance of solid build up and entrapped gas;
6. Depending on applicability, the necessary support should be provided, especially for large meters.

2.5.1 ORIENTATION AND MOUNTING

In this part meter mounting and orientation will be discussed briefly. Both horizontal and vertical orientations are allowed.

1. **Vertical orientation:** In vertical orientation flow should be in the flag up position, i.e., for upward flow. Flag up vertical mounting is always preferred as it helps in three ways:
   - The complete filled up condition is ensured;
   - Solids are drained downward;
   - In the case of liquid with entrapped gas, the gas can escape from the top.

   However, in certain cases downward vertical flow is also allowed. In the case of open downward flow, as with transfer of fluid from one reservoir there shall be a restricting orifice plate and valve in the downstream. This is to ensure that the line is not empty. Both these orientations have been shown in Fig. VI/2.5.0-1D.
2. **Horizontal orientation:** As stated earlier, horizontal orientation is acceptable for CMFM. There are two types of horizontal mounting: head up and head down, as shown in Fig. VI/2.5.0-1D. Head up installation is mainly used for liquids, whereas the head down option is normally selected for gas installations. In the case of a curved tube some precautions should be taken while measuring liquids. Head down orientation should be avoided if the liquid has solid contents so that they do not settle at the bottom at no flow and change the meter balance. Similarly, for liquid with entrapped gas, head down orientation should be avoided for the same reason, to avoid gas accumulation at the top.
3. **Inclined orientation:** Inclined orientations are seen in the case of offshore drilling.

2.5.2 GENERAL INSTALLATION DISCUSSIONS

1. **General rule for in-line meter installation:** As the Coriolis meter is an in-line meter, the general installation principles mentioned in earlier chapters are equally applicable here. As shown in Fig. VI/2.5.0-1A, there should be two isolation valves upstream and downstream of the meter so that the meter can be isolated whenever needed for maintenance, part replacement, etc. Naturally there should be one bypass line with a valve so that the process line remains unaffected while the meter is inoperative or is maintained. Another point to be borne in mind is that the meter should be placed just after (or before) the flange but no flange should be directly on meter housing, so a short meter section is needed.
2. **Transmitter types:** As discussed earlier, there are two kinds of transmitter, one is as an integral part of the Coriolis mass flow meter, i.e., integral with the sensor. The other option is a remote transmitter, where the transmitter is connected with the preamplifier of meter electronics by a cable connection as detailed in Fig. VI/2.5.0-1B.
3. **Position restriction:** As entrapped gas/air may be the cause of an error in measurement, for liquid measurement mounting of the meter at the highest point should be avoided so that there is no chance of gas accumulation. Similarly, a meter in a liquid application should not be placed upstream of the pipe free flow, so that the meter is not emptied (refer to Subsection 2.5.1.1). These avoidable locations have been depicted in Fig. VI/2.5.0-1C.
4. **Location:** A Coriolis meter should not be placed close to any valve which undergoes frequent ON—OFF operation. Frequent ON—OFF operation would cause pulsation and vibration, which affect greatly the performance of Coriolis meters.
5. **Piping:** Coriolis meters are greatly affected by stress and vibration in adjacent pipes, which should be avoided. For this the meter should be firmly connected to the piping and the piping should be properly clamped to avoid stress and vibration in the pipe.
6. **Heating:** There are certain fluids, e.g., HFO/LSHS that require heating to maintain flowability. Therefore, suitable care should be taken while installing the meter in these lines so that the electronics are not damaged and ambient temperature specified is not exceeded.

With this the discussion on installation of CMFMs is concluded.

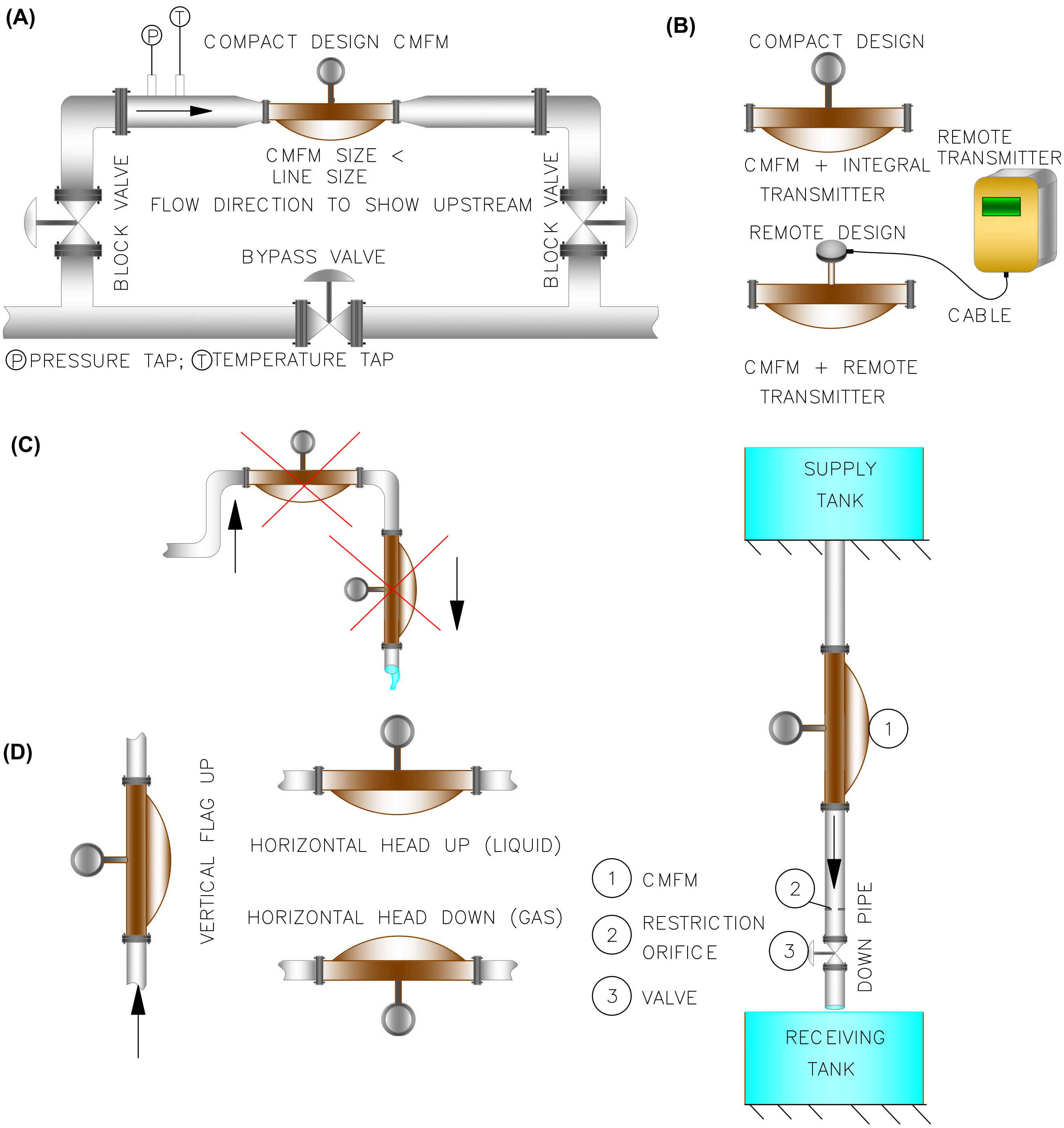

FIGURE VI/2.5.0-1 Installation of CMFM. (A) Typical CMFM installation. (B) CMFM transmitter versions. (C) Mounting location of CMFM (to be avoided). (D) CMFM orientation and installation styles.

2.6.0 Coriolis Mass Flow Meters Concluding Discussions

Short discussions on various issue related to the Coriolis meter are presented here.

2.6.1 ZERO CHECKING AND CALIBRATION

Zero checking and calibration are an important issue. There are a number of manufacturing

processes by which CMFMs are manufactured, therefore, the necessity of calibration of individual meters is inevitable to make adjustments to meet the specified accuracy and other performance data. Commonly water is used as the calibrating medium. Single medium calibration also received acceptance in the GRI-04/172 report of the Gas Research Institute in 2004. However, some manufacturers may have other advanced systems of calibration set up. In modern smart meters it is possible to get online verification of meter health.

1. **Zero checking:** Normally it is not required to check zero at the field, e.g., Micromotion claims that Elite meters mitigate the need for field zero calibration, however, as part of maintenance meters are verified for zero check. *At a minimum, inspection of the meter's zero should be performed seasonally in the first year of operation to identify any installation or process condition issues [4]*. Apart from this, in the case of any product build up or erosion/corrosion, zero checking needs to be carried out.
2. **Zero verification conditions:** For zero verification the following should be covered:
   - The meter is completely full;
   - For liquid measurement it is necessary to ensure that there is no entrapped air/gas or solids;
   - For gas flow it is necessary to ensure that there is no liquid present;
   - Pressure/temperature condition is within normal specification of the meter.

2.6.2 MISCELLANEOUS ISSUES

In this section a few miscellaneous issues are discussed.

1. **Sizing and pressure drop:** For a Coriolis meter pressure loss is a very important issue. The sizing of the meter is greatly affected by the pressure drop issue. Therefore, meters are often selected one size above what is required to deal with this situation.
2. **Sunlight exposure:** Coriolis meter performance is greatly affected by direct exposure to sunlight. So same should be placed under shed.
3. **Coriolis in gas flow measurement:** Coriolis meters are better suited for liquids than gases due to the low density of gases. Also, at low pressure gas flow measurement by Coriolis meter is not possible. From earlier discussions it is clear that the Coriolis meter becomes too expensive and unwieldy for sizes above 100 mm, which could be another issue for which it is less commonly used in gas flow measurement.
4. **Diagnostics:** Diagnostics of intelligent meters need special attention. Almost all meters have self-diagnostic features. Normally there are diagnostic indications (LED) to indicate the operating status of the sensor and transmitter-associated processor status. Also, it is possible through the operator interface to check the meter health. It also possible to check whether the sensor/transmitters are operating within their limits. In the case of a system fault diagnostic indicators alert for any damage to a sensor or other part of the meter. This is in addition to the process alarm. Some Coriolis sensor designs also provide online verification of the flow tube(s) structure [4].

Within the allowable pipe size for which a Coriolis meter is possible, it gives direct competition to other fluid meters, including electromagnetic flow meters which are the supposedly universal fluid meter. In fact, the Coriolis meter is preferred to other fluid flow meters in many applications. This is because of the fact that it can provide many parameters from a single unit and mass flow (with optional volumetric flow) is possible. This ends the discussions on Coriolis meter and we now look into other mass flow meter types.

3.0.0 IMPELLER TURBINE MASS FLOW MEASUREMENT

There are a few types of mechanical type mass flow meters. In this section the major types shall be discussed, including twin-turbine mass flow meters, gyroscopic mass flow meters, and impeller turbine mass flow meters. Discussions on twin-turbine meters have already covered in Subsection 3.1.4.2 of chapter I and hence are not repeated here. The gyroscopic mass flow meter is

another kind which uses the principle of a gyroscope. They can be used in slurry applications. However, on account of cost they are not so popular in industrial uses. The impeller turbine is another kind of mass flow meter which is often used, especially for aircraft fuel measurement. The principle of operation of the flow meter is very similar to hydraulic couplings used for driving speed control.

There are two moving elements in an impeller turbine flow meter: the impeller and rotating turbine. This arrangement has been depicted in Fig. VI/3.0.0-1 (top part).

In line with the constructional details, both of the rotating elements have annular channels through which fluid is directed to flow. The impeller is driven at a constant speed by a constant speed prime mover. Normally a synchronous motor is used as the constant speed prime mover for the impeller. The synchronous motor, through magnetic/eddy current coupling, drives the impeller to impart an angular velocity to the fluid flowing through the meter. There will be a turbine located downstream of the impeller. After leaving the impeller the fluid strikes the turbine, which is rotated against a restraining spring by the spin energy of the fluid. Therefore, the turbine receives a torque proportional to the angular momentum of the fluid (imparted by the impeller). As the turbine rotates against the restraining spring, there will be deflection of the spring. The angle by which the restraining spring deflects is proportional to the torque (hence angular momentum of the fluid), thus giving a measure of mass flow. This type of mass flow is used in a flight deck, where fuel flow is indicated as the meter gives a reading of the fuel mass flow rate in pounds or kilograms per hour. A typical fuel mass flow has been shown in the lower part of Fig. VI/3.0.0-1. Normally the turbine is connected to the transmitter rotor of a synchrosystem which will cause the pointer on the

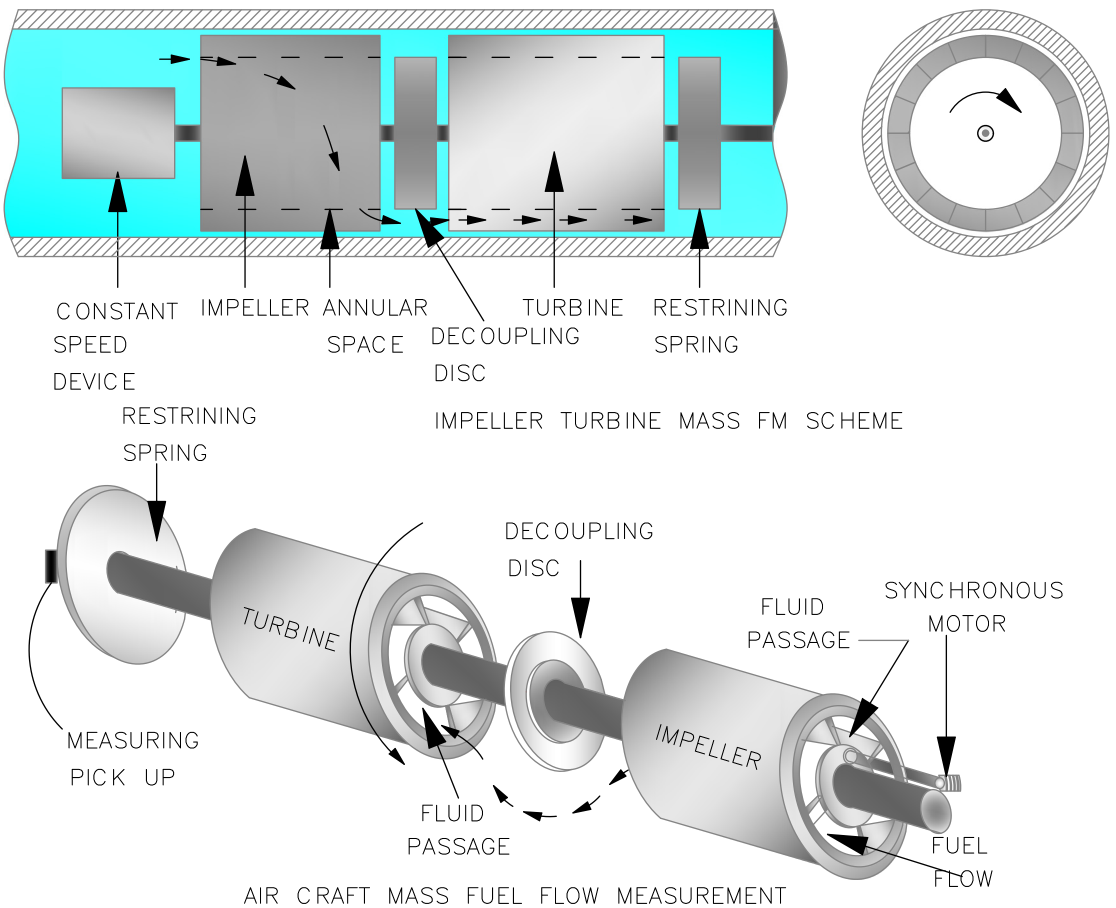

FIGURE VI/3.0.0-1 Impeller turbine mass FM.

flight deck gauge to rotate to the proper position to indicate the correct mass flow rate. There are various motorless fuel mass flow meters where an hydraulic driver is used. These are electronic with accuracy as high as 0.5% AR. These meters can operate over a wide temperature range of −55 to 200°C. the meters are available in various flow ranges: 32 kg/h to 1361 kg/h or 59 kg/h to 2722 kg/h, and 127 kg/h to 20,866 kg/h so that these meters can cover a wide range of applications from commuter jets to transportation applications, i.e., ELDEC fuel flow meters (courtesy of Eldec).

Other than a mechanical system, it is possible to measure mass flow by a thermal method also. This is discussed in the following section.

4.0.0 THERMAL MASS FLOW MEASUREMENT

Thermal mass flow meters can be deployed for measurement of mass flow for slurry, liquid, and gases. However, thermal mass flow meters are mostly used in gas applications because other types of gas flow meters are greatly influenced by fluid density and other properties, so the other kinds of gas flow meters cannot directly measure the mass flow rate. Therefore, process pressure and temperature need to be measured for accurate "density" correction. In contrast, thermal flow meters based on convective heat transfer effects can measure directly and accurately mass flow of fluid. Also, commonly used industrial thermal dispersion type flow meters are not suitable for liquid because at zero flow, on account of the high conductivity of liquid compared to gas, major heat is taken up by the fluid, making the sensing insensitive. Also, in most cases higher ΔT cannot be used to avoid cavitations. Therefore, during discussions references may often be given for gas flow. Depending on the applicability they can be used for liquid cases also. Thermal mass meters are economic and are available for a wide range of flow rates. These flow meters are independent of process conditions (but may have some dependence on gas properties). For these reasons thermal flow meters enjoy a significant advantage over others. Therefore, flow meters can be calibrated at ambient conditions for one specific gas, but can be used at process conditions without the necessity for density corrections. Thermal mass flow meters are classified as shown in Fig. I/3.1.4-3. According to this figure, there are basically two types of thermal mass flow meters: heat transfer and hot wire types.

1. **Heat transfer and capillary tube thermal mass flow meter:** In heat transfer type thermal mass flow meters, heat energy is transferred to the bulk, or to all of the fluid flowing through the tube in question. Thus this type of flow meter measures the change in temperature of the fluid after a known amount of heat has been added to the bulk of the fluid. In heat transfer types there are two options, namely, direct and bypass types. Of these two, the direct type can rarely be used on account of certain limitations discussed later. The bypass type deploys a capillary tube in the bypass line. Therefore, this type of mass flow meter is known as a ***capillary tube*** thermal mass flow meter. This type of flow meter is noninvasive.
2. **Hot wire/dispersion type thermal mass flow meter:** Hot wire type thermal mass flow meters are also known as "industrial thermal mass flow meters," "immersible mass flow meters," or "thermal dispersion type (thermal) mass flow meters." In this type of thermal mass flow meter measurement is carried out on the basis of the effect of flowing fluid on a hot body (hence hot wire). There is a heated surface of a cylinder immersed in the flow stream. The heated surface of the cylinder transfers heat to the viscous boundary layer surrounding the cylinder. This type of flow measurement is an invasive type of meter and there will be a small pressure drop in the system due to this.

Therefore, it is clear that the theoretical models expressing the first law of thermodynamics for each type of thermal mass flow meter are not the same [10]. There has been wide use of thermal mass flow meters in industry, especially in the semiconductor industry. Therefore, development of a theoretical model is now demanded so that these models can predict meter performances for different gases, including hazardous gases. Naturally for this it is necessary to have some knowledge about the physics behind the operation of these models. Short discussions on the theoretical background of these two types shall now be discussed.

4.0.1 THEORETICAL BACKGROUND OF HEAT TRANSFER MASS FLOW METERS

Let us look back at our old school days to recap on calorimetry. It is known that heat gain or heat loss (H) between two bodies can be expressed as $H = m \cdot s \cdot \Delta T$, where m represents the mass of the body gaining/loosing heat, s is the specific heat of the same body, and ΔT is the temperature difference between the two bodies between which heat flow takes place. From this it is could be inferred that $m = H/(s \cdot \Delta T)$ or mass flow rate $m/t = H/(s \cdot \Delta T) \cdot t$, which suggests that if the heat transfer amount and specific heat of the body are known, then by monitoring ΔT, it is possible to calculate the mass flow rate.

1. **Direct design with external arrangement:** The operation of the heat transfer flow meter is based on Eq. (I/3.1.4-7). When *rewritten* for this section it is:

$$q_m = H/\{C_p \cdot (T_2 - T_1)\} \qquad \text{(VI/4.0.1-1)}$$

considering, H as heat per unit time. With reference to Fig. I/3.1.4-3, it can be seen that as long as C_p for the fluid is known and a constant current heater is used (i.e., power to the heater is constant and known), by monitoring the temperature differences the mass flow rate can be computed. In order to circumvent the erosion and corrosion issue, external heating and sensing systems were adapted.

- *Heated tube design:* In order to avoid corrosion, erosion, and the possibility of a coating effect i.e. to protect the heater and sensor elements, a heated tube design has been developed as shown in Fig. VI/4.0.0-1. Here, the heaters and sensors are external to the tube. The sensors respond slowly to the change in heat. In this type of construction, the heat transfer mechanism becomes more complicated [1].
- *Nonlinear relationship:* The relationship between mass flow and temperature difference is nonlinear. This nonlinear relationship is obvious because the heat injected by the heater is distributed over some portion of the pipe's surface and then transferred to the process fluid at varying rates along the length of the pipe. The pipe wall temperature is highest near the heater downstream, however, at some distance away (from the heater), there is no difference between the wall and fluid temperatures. If the downstream temperature sensor is T_2 and the upstream unheated fluid temperature is T_1 (as detected by the upstream sensor located some distance away from the heater). Then the relationship of heat transfer and mass flow rate would be:

$$q_m^{0.8} = H/\{C_p(T_2 - T_1)\} \qquad \text{(VI/4.0.1-2)}$$

where H is considered as heat per unit time. (*This equation may be compared with* Eq. I/3.1.4-9.) At this point Eq. (VI/4.0.1-2) may be compared with Eq. (VI/4.0.1-1) to see the nonlinearity. As one can see, there are two parameters, H (proportional to heating power) and $\Delta T(=T_2 - T_1)$, that keep one parameter constant while the other can be varied to compute mass flow rate. The two modes are:

- *Constant current/power mode:* In the constant current mode, mass flow rate is measured, by measuring the temperature difference, keeping the electric power input constant.

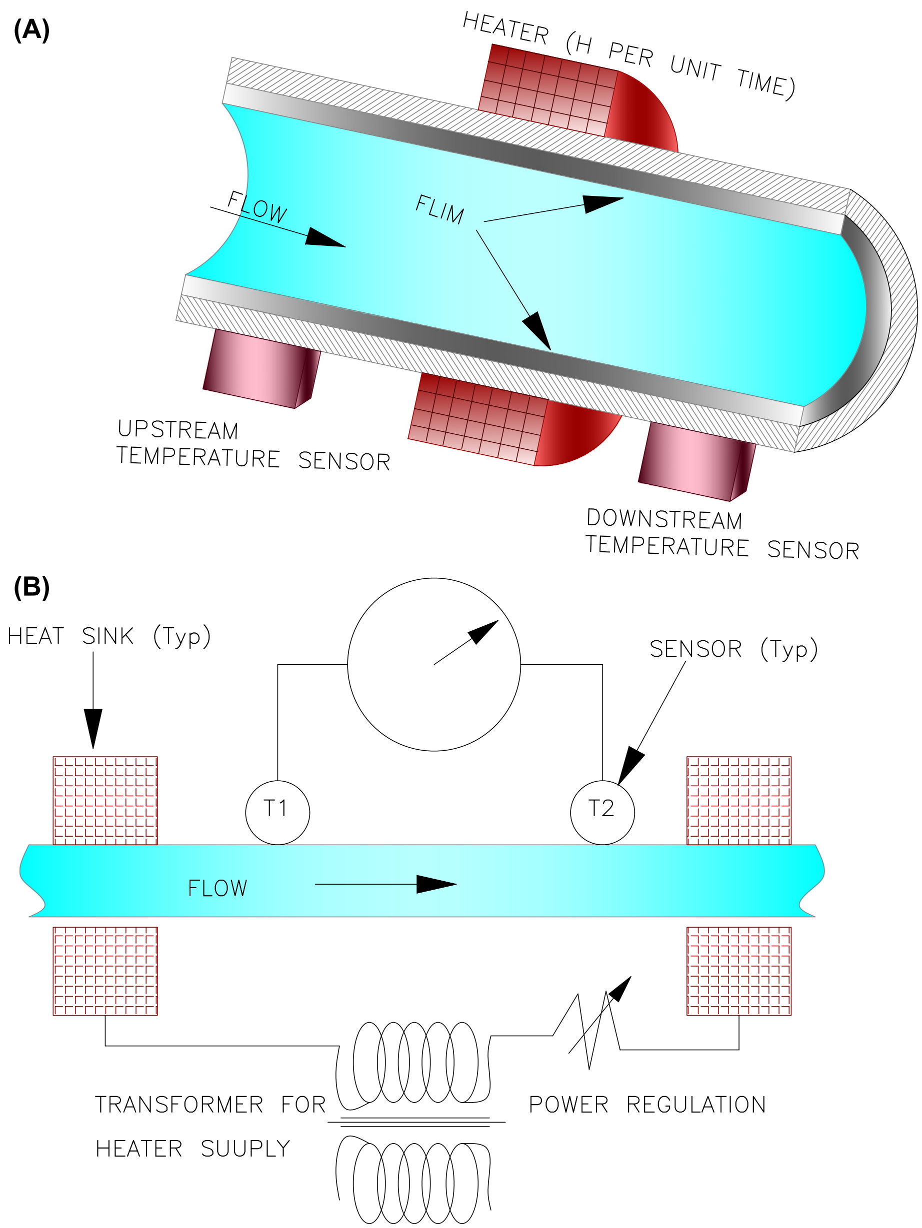

FIGURE VI/4.0.0-1 External arrangement for heat transfer TMFM. (A) Tube with external elements. (B) Heated tube design.

- *Constant temperature difference mode:* In this mode, the mass flow rate is measured by measuring the power (i.e., current) needed to maintain the constant temperature difference. This is the constant temperature difference mode. In this mode a wider range can be covered.

  The main advantage of this system is that it is noninvasive and nonintrusive measurement, and hence there is no pressure drop.

2. **Bypass design with external arrangement:** Heat transfer types with bypass designs are used for measurement and control of larger flow rates. Bypass thermal mass flow meters consist of a capillary sensor bypass tube connected to the main flow tube/conduit. The sensor bypass line consists of a thin-walled capillary tube and external heating and sensing unit. The capillary tube is of diameter 3 mm (0.125″) with a very low wall thickness of

0.051 mm (0.002″). There can be two or three external windings. In the case of three windings, the center one is used as a heater for transferring heat to the fluid through the thin capillary wall. The other two are upstream and downstream of the heating element RTD sensors for monitoring temperature differences. Alternatively, there could be two identical externally wound self-heating platinum RTDs meant for both heating the tube and measuring the resulting temperature rise. These two identical PRTD coils have a constant and equal amount of current through them and are in turn heated up. In such a case, variation in fluid flow temperature compensation may be given separately. In any case the measurement of temperature rise/difference is done in a Wheatstone bridge. The meter is called a bypass type because a defined portion of the flow is bypassed and a constant ratio of bypass flow to main flow is maintained. This condition will only apply if the flow in the bypass is laminar so that the pressure drop across the bypass is linearly proportional to the bypass flow [6]. The typical arrangements for a bypass flow meter have been depicted in Fig. VI/4.0.0-2.

The meter is placed in a bypass around a restriction in the main pipe and is sized to operate in the *laminar flow* region over its full operating range [11]. Mainly the laminar flow element in the main line is maintained. It not only maintains the laminar flow but also acts as a restriction to force a part of the main flow in the bypass line for measurement. The laminar flow element is good for clean fluid (gas), if there is the possibility of contaminants, or a smaller sensor tube is used then it is necessary to use a filter separately. When laminar flow is maintained in the main as well as the bypass line, then the ratio of flow rates in both paths will maintain a constant ratio. There could also be an orifice for bypass. In the case of an orifice there will be nonlaminar flow, so the ratio of total flow to sensor flow is nonlinear. Both arrangements have been shown in laminar

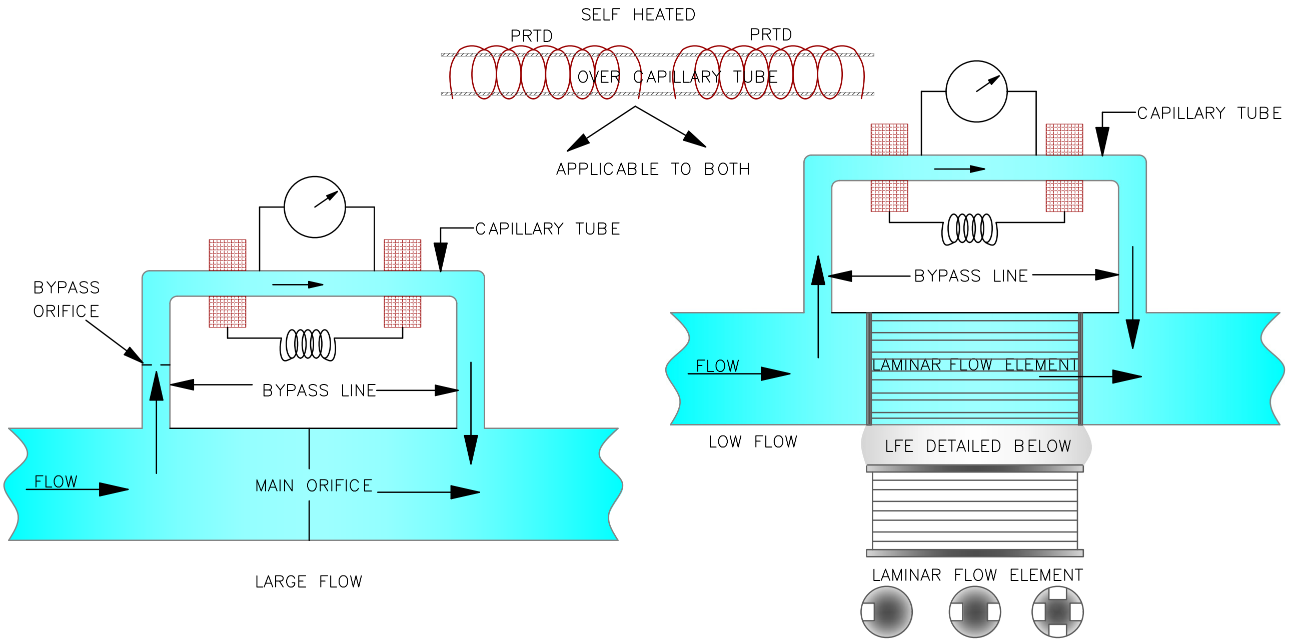

FIGURE VI/4.0.0-2 Bypass design with external heating TMFM. *Developed based on M.A. Crabtree, Industrial Flow Measurement, The University of Huddersfield, June 2009. http://eprints.hud.ac.uk/5098/1/macrabtreefinalthesis.pdf&sa=u&ei=v66ttp_ccojmialag7mnbq&ved=0cdiqfjat&usg=afqjcngao5vc1jsrrbjucjvkxotjjoah6q.*

flow, the element is a machined element with a number of rectangular flow passages. Rectangular flow passages have a high length to width ratio, e.g., Sierra instruments use radial slot design laminar flow elements, where flow axially enters the inner passageway of an annular laminar flow element with a multiplicity of small radial channels. A laminar flow element has been detailed in Fig. VI/4.0.0-2. When there is no flow, the heating elements raise the bypass tube temperature to approximately 70°C above the ambient temperature. At no flow, the temperature differential between the upstream and downstream sections is zero on account of the symmetrical temperature distributions along the length of the tube. In the case of flow, the fluid molecules carry the heat downstream, i.e., flowing fluid will carry heat from upstream toward downstream sections of the sensor tube. Thus there will be changes in resistance proportional to temperature and hence proportional to the mass molecular flow of the fluid medium. For this reason the temperature profile is shifted in the direction of flow. Wheatstone bridge connected to the sensors converts the electrical signal due to change in resistance into a mass flow rate (proportional to the change in temperature). The smaller the diameter of the sensor, the better the response time and the lower power requirement. A smaller diameter however, also has a higher danger of impediment-related failure [1]. There are two types of sensor tubes, straight and U tubes, each with pros and cons. The U tube design is a compact one and straight tube designs provide better cleaning facility and give stressfree conditions. This type of sensing system has a moderate accuracy of 2% AR. One thing worth noting here is that this arrangement calls for higher pressure loss, and hence is more suitable for high-pressure gas applications, where in any case pressure reduction is inevitable [11]. The old analog systems have now been replaced by smart digital systems and the system can now easily accommodate controllers and digital control systems.

4.0.2 THEORETICAL BACKGROUND OF THERMAL DISPERSION MASS FLOW METERS

The other type of thermal mass flow meter is the thermal dispersion type flow meter, which is mainly deployed for large flow measurements in process and other industrial plants. Greater numbers of participants, including large instrument manufacturers, offer this type of flow meter. However, prior to starting the discussions on this type it is better to recapitulate a few terms related to heat transfer and fluid mechanics. These will be necessary for subsequent discussions. It is worth noting only *working definitions/explanations* could be accommodated here within the limited space of this book. For further details a standard book on heat transfer may be referred to. Here these details are given so as to enable readers why there will be non linearity in heat distribution (and associated influencing factors and issues).

1. **Discussions on a few related terms:** When the question of solutions of a series of system equations related to fluid mechanics and heat transfer, people often are bogged down in handling a number of engineering units and their conversions. Therefore, it is always better to nondimensionalize the equations to solve them quickly. However, these solutions are not real issues but theoretical ones. To arrive at the real issue one needs to apply variations and constraints. Thus keeping a few parameters fixed or constant and varying others will model the real problem. A few constants listed below are similar, such as constants used in heat transfer and fluid dynamics problems. Therefore, these nondimensional numbers are helpful tools for solving system equations. Like Reynolds number (refer to Chapter I) there are a few other dimensionless numbers that are important for fluid mechanics and heat transfer problems that are covered here. As the thermal dispersion type flow meter is related to heat transferred through convection, the terms discussed here are related to that.

- *Nusselt number (Nu):* Nusselt number (Nu) is a nondimensional heat transfer coefficient. The Nusselt number gives the comparison between the conduction and convection heat transfer rates. Nusselt number (Nu), may be defined as the ratio of convection heat transfer to fluid conduction heat transfer under the same conditions, i.e., it is the ratio of heat transferred through convection (fluid motion) to the heat transferred through conduction (stagnant).

  Nu = hL/λ where h represents convective heat transfer coefficient, L is a representative dimension (for pipe diameter unit of length), and λ is the conductivity of the fluid. Nu is a measure of the ratio between heat transfer by convection (h) and heat transfer by conduction alone (λ/L). Fluid motion always helps for heat transfer. Therefore Nu helps us to understand how much the heat transfer is enhanced due to fluid motion. Nu is always >1 as fluid motion assists heat transfer. Note that the fluid motion always results in an increase in heat transfer and hence Nu is always greater than 1 for convection. Nu is more qualitative than quantitative. Therefore Nu helps us to compare different configurations and to assess heat transfer performance. Nu is a function of Reynolds number and Prandtl number.
- *Reynolds number:* Refer to Section 1.1.2 of Chapter I.
- *Prandtl number:* The Prandtl number is a dimensionless number approximating the ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity and can be expressed as $\mathbf{P_r = v/\alpha}$; where Pr = Prandtl's number; v = momentum diffusivity (m^2/s); α = thermal diffusivity (m^2/s). The Prandtl number can also be expressed as $\mathbf{P_r = \mu C_p/\lambda}$; where, μ = absolute; λ = thermal conductivity; C_p = specific heat; Prandtl number which is dependent on fluid property, is used for heat transfer and free and forced convection. Values may vary with fluid such as: *Gases*—P_r ranges 0.7−1.0; *Water*—P_r ranges 1−10; *Oil*—P_r ranges 50−2000; *liquid metals*—P_r ranges 0.001−0.03.
- *Grashof number:* The Grashof number (Gr) is a dimensionless number. It is the ratio of the buoyancy to viscous force acting on a fluid, i.e., $Gr = \frac{\text{Buoyancy force}}{\text{Viscous force}}$. This dimensionless number is used in the correlation of heat and mass transfer due to thermally induced natural convection at a solid surface immersed in a fluid. Grashof number represents the ratio between the buoyancy force due to *spatial variation in fluid density* (caused by temperature differences) to the *restraining force* due to the viscosity of the fluid.
- *Knudsen number:* In gas dynamics this is the ratio of molecular mean free path to some characteristic length (d).
- *Mach number:* Mach number refers to the speed of sound traveling through a medium. **Mach 1 = 330 m/s**. So in the case of compressible fluids:
  - Velocities <330 m/s i.e., **Subsonic**; M < 1, density is relatively *constant*;
  - Velocities ≃ 330 m/s i.e., **Transonic**; M ≃ 1, density change ≃ *velocity change*;
  - Velocity >330 m/s i.e., **Supersonic** M > 1, *density change faster than velocity by* M^2.

  These constants will be used in mathematical deduction of equations for meters later in this chapter. Now let us gather knowledge on thermal dispersive flow meter operation.

Apart from the above dimensionless constants there are a few other terms also important which will be used in this type of thermal mass flow meter. These are:

- *Skin resistance:* This is the thermal resistance of the intervening layer of material or skin in the heated section of velocity sensor embedded in the heated RTD and external surface.

- *Sensitivity:* This is the slope of the nonlinear curve generated when the output of the meter is plotted against mass flow.
- *Stem conduction:* This is a kind of heat loss from the velocity sensor due to heat conduction to the external ambience through the stem of the velocity sensor.

2. **Thermal dispersive mass flow meter:** Thermal dispersion type sensing is also known as immersible thermal sensing as it is completely immersed into the flow stream. For gas flow measurement it can measure higher gas flow rate at much harsher conditions. This is possible because there will be very little pressure drop since it does not have to pass through the laminar flow element (or orifices). Complying with the name, the philosophy of measurement uses the flow rate-dependent heat transfer from a heated body to the flowing medium mainly gas (*refer to the initial discussions in this section, where it has been indicated that this type of sensor is not much suited to liquid*). Another important issue to address is that this flow rate-dependent cooling is *not* as a function of pressure and temperature. Measurement mainly depends on the type and number of fluid molecules that get into contact with the hot surface [5]. In this method the mass flow rate of the measuring medium is measured directly. However, the gas property and hence calibration parameters have a direct bearing on the measurement process. Basically, the flow meter consists of two precision platinum resistance temperature detectors (PRTDs) duly protected by a sheath (platinum-iridium sheath for Sierra). Of the two PRTDs, one is meant to sense the temperature of the gas, while the other is meant to sense the flowing medium velocity. The velocity sensor is normally kept at a higher temperature (about 40°C) above the gas temperature sensor by electrical heating. As the gas flows, the cooling of the velocity sensor due to gas flow is measured to arrive at the mass flow rate. Thermal dispersion meters could be in-line type or insertion type as shown in Fig. VI/4.0.0-3.

   There are two modes of operation of this sensor:

   - *Constant power mode (CPM):* In CPM the power (hence current for I^2R) to the sensor is kept constant and the measured value is ΔT;
   - *Constant temperature mode (CTM):* In CTM a constant temperature is maintained by supplying additional power to the system to compensate for the heat taken away by gas, to maintain a constant temperature differential ΔT between the temperature sensor and the velocity sensor. In this mode the output signal is electrical output power W. CTM is the more popular mode of operation.

From the first law of thermodynamics, (which takes into account the conversion of heat into work and vice versa) is applied one gets that.

electrical power W can be related to heat taken away from the sensor by convection (H_c) and conduction (H_L) method as per Eq. (VI/4.0.2-1)

$$W = H_c + H_L \qquad \text{(VI/4.0.2-1)}$$

The heat quantities, H_c and H_L, depend on the gas properties and detailed treaties are necessary. Various dimensionless quantities discussed in Subsection 4.0.2.1 would be necessary to find the heat transfer quantities. In 1914, King derived a solution for the heat transfer from an infinite cylinder to derive an equation relating the heat transfer coefficient with fluid velocity v as

$$\text{King's law: Heat coefficient } h = a + b \cdot v^c \qquad \text{(VI/4.0.2-2)}$$

where a, b, and c are calibrating constants c (∼0.5).

Utilizing King's law relation of power output and mass flow has resulted in Eq. I/3.1.4-10. Various constants given there will come from the heat transfer equations. Thus the heat transfer

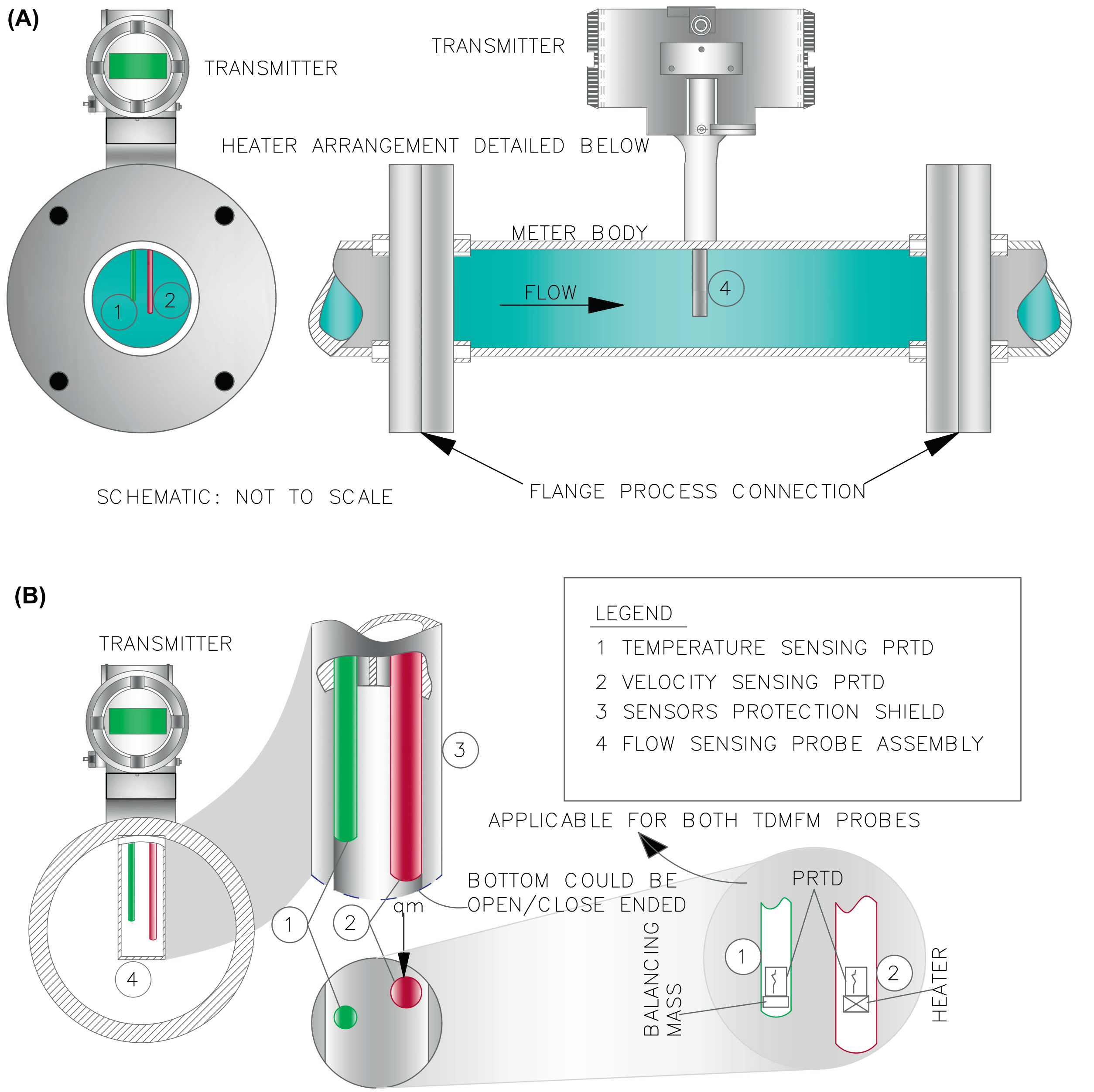

FIGURE VI/4.0.0-3 Thermal dispersion TMFM. (A) Inline thermal dispersion TMFM. (B) Insertion type thermal dispersion TMFM. *Developed based on an idea from Sierra instruments.*

from flowing gas is affected by properties of the gas thermal conductivity, density and viscosity, and heat capacity/heat transfer coefficient. Therefore it is necessary to understand and account for all these issues for thermal meter to assure accuracy. All these details are discussed later (Subsection 4.2.1.5) in this chapter.

4.1.0 Capillary (Bypass Heat Transfer) Thermal Mass Flow Meters

With the basic theoretical background discussed in the previous Section 4.0.1 we now look into little more details about the meter with some mathematical treaties.

Capillary meters are available as normal meters or available as a mass flow controller with a control valve along with integral control electronics. These are available for gas as well as liquid flow, mainly in the low-flow range, e.g., LIQUIFLOW of Bronkhorst BV. We now start discussions with some mathematical expressions.

4.1.1 FORMULA DERIVATION FOR CAPILLARY THERMAL MASS FLOW METERS

1. **Mathematical derivation of the formula:** From the discussion in Subsection 4.0.1.2 it can be seen that after entering the gas in the meter, it is divided into two flow paths. The vast majority of the gas (q_{m2}) flow passes through Laminar flow element (*LFE*). A very small portion of the total flow (q_{m1}) is diverted through a small "capillary" sensor tube. Now the measurement takes place in the sensor tube, from which one needs to calculate the total mass flow rate q_m. So it is necessary to relate and express q_{m1} in terms of q_m. Measured q_{m1} can be expressed as:

$$q_m = q_{m1} + q_{m2} \text{ or } q_m = q_{m1} \cdot (1 + q_{m2}/q_{m1}) \text{ or } q_m = k_1 \cdot q_{m1} \quad \text{(VI/4.1.1-1)}$$

here, the constant k_1 is hardly calculated, normally k_1 is discovered as the calibration constant during full-range calibration for an individual instrument. The measurement is affected by the flow profile, fluid viscosity, and pressure. Also, the measurement is determined by the thermal characteristics of the fluid; the system must be calibrated for each particular gas for each instrument over the entire flow range. One should accept that this is a limitation of this method [6]. To apply the first law of thermodynamics for energy balance, one has to look at the heat transfer, which from Subsection 4.0.1.2 clearly has two heat transfer areas:

- The temperature distribution of the tube;
- The temperature distribution of the gas inside the tube.

The measured value is nonlinear. To find the actual distribution of temperature for the tube and the gas, complex differential equations with two dependent variables need to be solved. Such solving of two differential equations is too complex and not an absolute necessity for our purpose. Instead if we select a very small sensor tube and restrict the mass flow rate through the tube (q_{m1}) by careful selection of our LFE bypass, then we limit the solutions of these equations to a narrow linear range over (of interest to us) which q_{m1} is directly proportional to ($T_2 - T_1$); where the average temperature of the downstream coil is T_2 and that of the upstream coil is T_1. Also, here it is assumed that the electrical power and the thermal losses are constant, and that gas does not travel so fast that it cannot absorb all of the applied heat. When the mass flow rate and temperature difference for a particular gas are plotted one would expect to get a plot as shown in Fig. VI/4.1.0-1D. As stated above, for any particular gas, if we choose only the linear portion of the curve in Fig. VI/4.1.0-1D then we have for any given gas:

$$q_{m1} C_P = c_1 (T_2 - T_1) \quad \text{(VI/4.1.1-2)}$$

where C_P = the coefficient of specific heat for the given gas; and c_1 = a constant for the meter applicable to all gases [10] (in the linear range only). Substituting $q_m = k_1 q_{m1}$ from Eq. (VI/4.1.1-1) into Eq. (VI/4.1.1-2) above, we get:

$$q_m / k_1 C_P = c_1 (T_2 - T_1) \quad \text{or} \quad q_m \cdot C_P = k_1 c_1 (T_2 - T_1) \quad \text{or}$$

$$\mathbf{q_m \cdot C_P = c(T_2 - T_1)} \quad \text{(VI/4.1.1-3)}$$

where, $c = k_1 c_1$ and a meter constant applicable for all gases in the chosen range. Now the objective is to find, as in all other cases where one needs to derive one dimensionless factor, e.g., k_m by applying the equation for a special case, so that the same factor can be

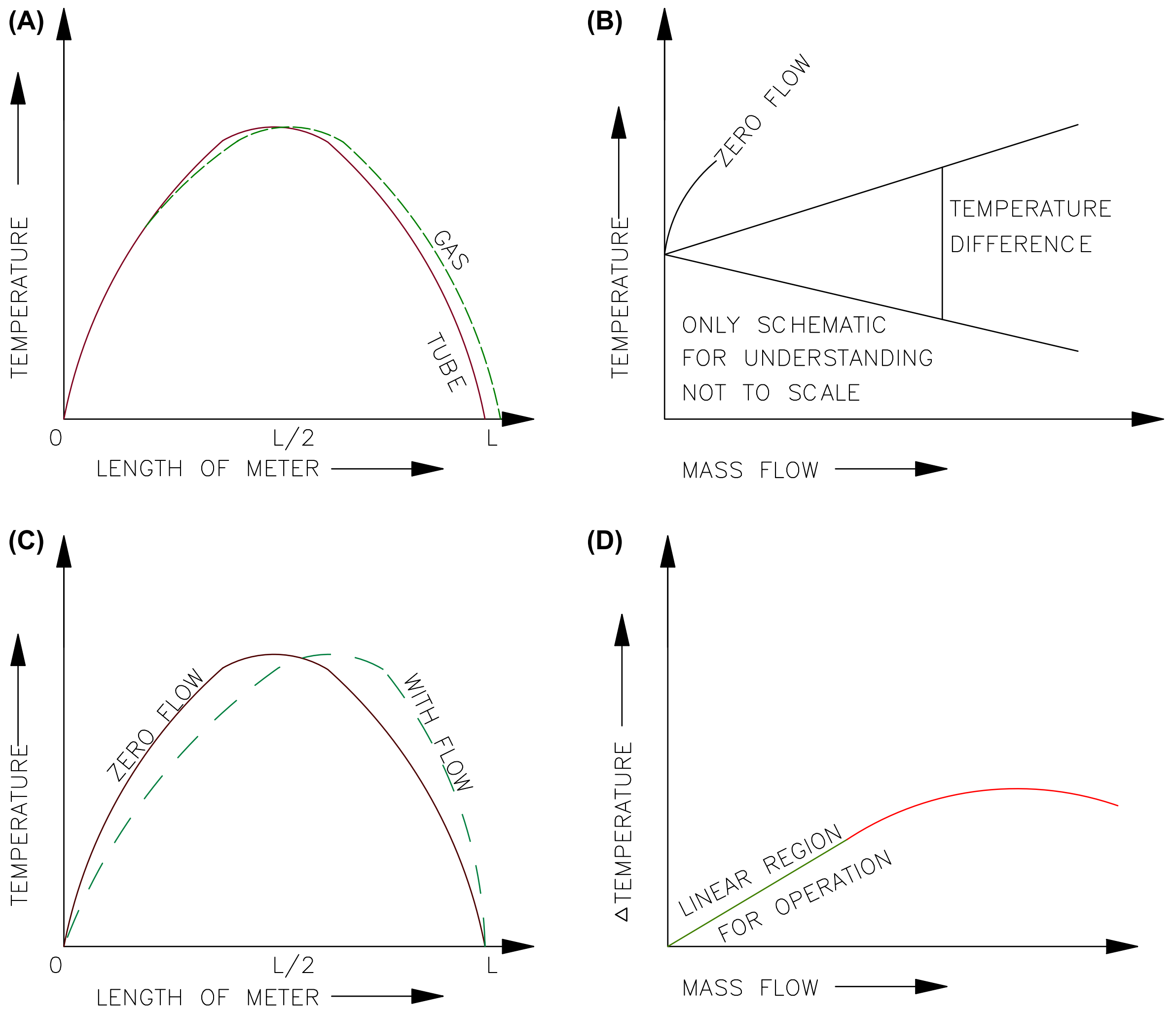

FIGURE VI/4.1.0-1 Characteristic curves for capillary TMFM. (A) Temperature distribution. (B) Temperatures versus flow. (C). Temperature offset. (D) Temperature−flow characteristics.

utilized in a generalized way (as we do for all other constant numbers). Let us for a special case take N_2 as the reference gas duly represented by suffix "r." For this case, Eq. (VI/4.1.1-3) can be rewritten as:

$$q_{mr} \cdot C_{Pr} = c(T_2 - T_1)[\text{where } c = k_1 c_1] \qquad \text{(VI/4.1.1-4)}$$

Let any measuring gas for the meter, similarly be represented by "g." Now applying Eq. (VI/4.1.1-3), we get:

$$q_{mg} C_{Pg} = c(T_2 - T_1)[\text{where } c = k_1 c_1] \qquad \text{(VI/4.1.1-5)}$$

If we divide Eq. (VI/4.1.1-5) by Eq. (VI/4.1.1-4) for the same output signal $T_2 - T_1$, we get:

$$\frac{q_{mg}}{q_{mr}} = \frac{C_{Pr}}{C_{Pg}} = k_m \qquad \text{(VI/4.1.1-6)}$$

where k_m is a dimensionless k-factor used for the measurement of mass flow rate in units of g/s or kg/s [10].

Basically, the measurement is not linear, but by choosing a linear range, the solution is simplified and workable. In spite of the complexity in deriving the formula for mass flow computation, this meter offers a few

advantages, such as wide rangeability (1000:1), low speed sensitivity. and faster response time (typically 2 s) [6].

2. **Meter characteristic curves:** After mathematical deduction it is important to have a look at various characteristic curves for physical interpretation. For this let us refer to Fig. VI/4.1.0-1.
   - *Fig. VI/4.1.0-1A:* This figure shows the typical distribution of temperature of the tube shown by a continuous (maroon) line and the same for gas is represented by a dotted (green) line. Both almost follow the same curvature with a slight offset to show a small delay in sensing. In the first section there is a rise in temperature with the peak at the middle (due to both heating by gas from the first heater and the second heater), as the gas takes away heat the temperature falls in the second half and reaches almost zero at the capillary end.
   - *Fig. VI/4.1.0-1B:* On account of gas flow the temperature of T_1 falls as the flow increases and it is carried towards the second sensor so its temperature rises, creating a difference between the two sensors. In other way it corroborates with Eq. (VI/4.1.1-4) (in the linear range considered).
   - *Fig. VI/4.1.0-1C:* The explanation is similar to that for Fig. VI/4.1.0-1A, here there is an offset between $q_m = 0$ and when $q_m > 0$. At some positive flow, part of the heat is taken away so it takes longer, and hence the length to attend the peak temperature creates an offset.
   - *Fig. VI/4.1.0-1D:* This is of more interest to us. It is seen that the curve is not linear for all flow quantities. Since by suitable selection we need to operate the meter in a linear region, high flow measurement cannot be achieved in this meter as at high flow it has nonlinear characteristics.
3. **Volume flow computation:** In Subsection 4.1.0.1 we have derived the mass flow with respect to difference in temperature between two sensors. Now if we consider the standard condition, i.e., STP (refer to Fig. I/1.1.2-3),

$$q_m = \rho_s \cdot q \qquad \text{(VI/4.1.1-7)}$$

where ρ_s = the density of the gas at STP; q = the volume flow rate of the gas at STP.

From Eq. (VI/4.1.1-6) we get $\frac{q_{mg}}{q_{mr}} = \frac{C_{Pr}}{C_{Pg}}$. Substituting the value of q_m from Eq. VI/4.1.1-7 we get: $q_{mg} = \rho_{gs} \cdot q_{gs}$ and $q_{mr} = \rho_{rs} \cdot q_{rs}$. Here all suffixes are the same as those used in Subsection 4.1.1.1, only an additional suffix s is added to indicate STP.

$$\frac{\rho_{gs} \cdot q_{gs}}{\rho_{rs} \cdot q_{rs}} = \frac{C_{Pr}}{C_{Pg}} \quad \text{or} \quad \frac{q_{gs}}{q_{rs}} = \frac{C_{Pr}}{C_{Pg}} \cdot \frac{\rho_{rs}}{\rho_{gs}} = k_v \qquad \text{(VI/4.1.1-8)}$$

where k_v is dimensionless k factor to express volume flow in slpm and sccm, and where "s" represents the STP condition. When mass flow measurements are so advantageous then why is volume flow necessary? The answer is very simple, in case of low gas flow, expressing the same in mass flow units is very difficult to conceive. An example will make this clear. The approximate density of air at STP is nearly 1.293 g/L. For 50 slpm, the mass flow will be nearly 64.65 g/min. Therefore, it is difficult to understand mass flow than volume flow. So in the case of low gas flow, it is better to specify in SLPM than kg/min, etc. and hence this will be described accordingly in this section on flow range specifications for gas.

4.1.2 DESCRIPTIVE DETAILS OF CAPILLARY THERMAL MASS FLOW METERS (TMFM)

Capillary thermal mass flow measurement systems are available in two forms, one is the capillary thermal mass flow meter, which provides mass flow output. As already mentioned there is another version which includes one controller and an integral valve along with a capillary TMFM. This is better known as the capillary thermal mass flow controller. Both the versions have the necessary electronics as

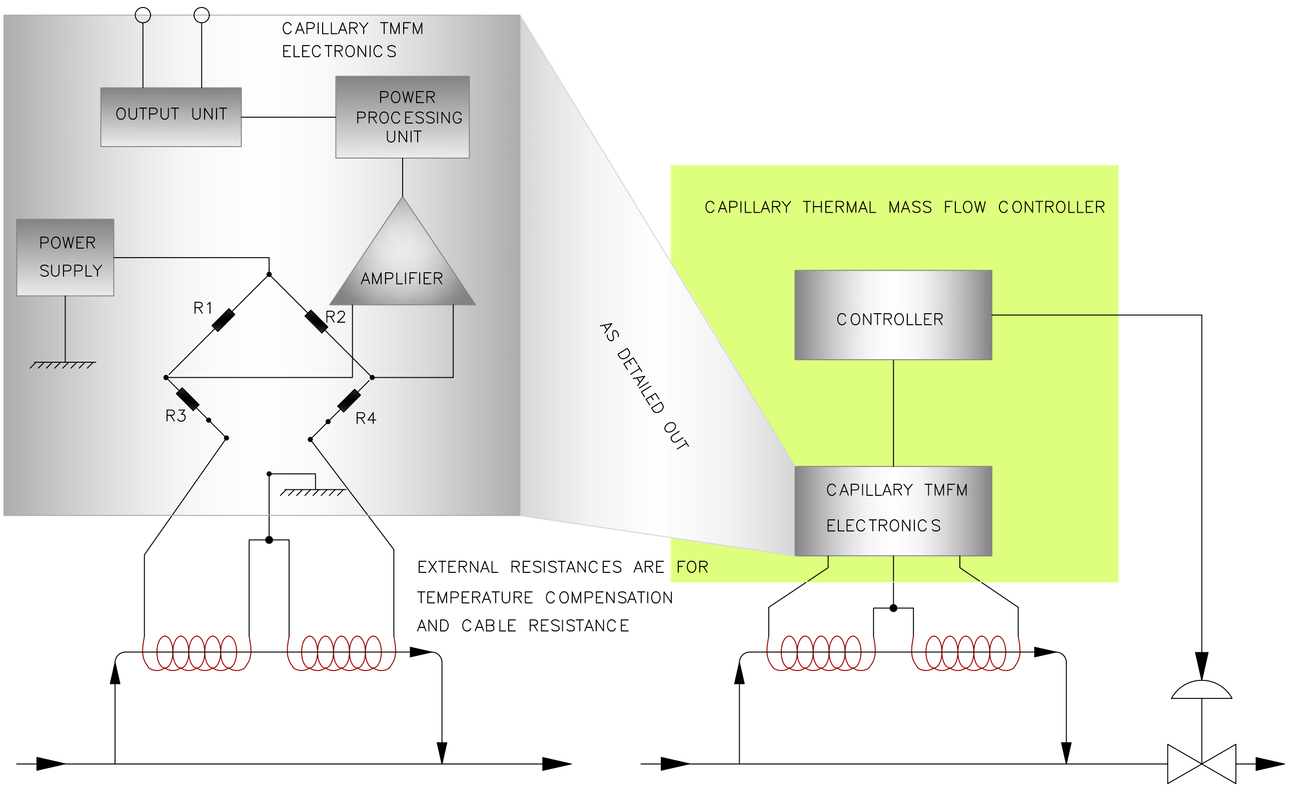

FIGURE VI/4.1.0-2 Capillary TMFM and TMFC.

depicted in Fig. VI/4.1.0-2. Application areas of capillary thermal mass flow-measuring systems are general industrial applications as with other flow meters. A special application area of this meter is its application in the semiconductor industry. In most the semiconductor industries capillary thermal mass flow controllers are used.

Normally a capillary thermal mass flow meter system consists of the following components. In the case of TMFC, additionally, there will be a controller and an integral valve:

- Flow conditioning;
- Flow meter body;
- Bypass;
- Sensor tube;
- PRTDs;
- TMFM electronics;
- Controller (TMFC only);
- Integral valve (TMFC only).

In this section brief details of these shall be discussed. In the case of semiconductor application there are some special requirements as listed below:

1. **Requirements for semiconductor applications:** In the case of semiconductor manufacturing applications, there are some essential special requirements. Any impurities would cause complete wastage of the product. The author had the opportunity to work for VSI semiconductor project Chandigarh India for class 10 purity level. Typical such requirements are listed below:
   - No particulate or other contaminant of specified size in microns should enter the fabrication process. They use a particle filter;
   - Toxic or any other undesired gas escape—meaning high sealing;
   - Ultrapure air and water are used in semiconductor manufacturing facilities, however, there could an air leakage in the process.

   Therefore it is essential that there would be upstream and downstream shut-off

valves to quickly isolate the system. Meters/controllers must have upstream particulate filters.

2. **Flow conditioning:** In order to eliminate flow profile distortions due to upstream obstructions such as an elbow, etc. it is necessary to use a flow conditioner, especially for higher flow rates. Flow conditioning helps in creating laminar flow. As changes in the downstream flow profile do not affect the measurement so the same is not necessary at downstream. After flow conditioning a tortuous flow is created in the meter to effectively erase any nonuniform past history of the flow [12]. There are settling chambers used to further flatten the flow. There would be an inlet filter/screen that captures the remaining particulate. After all these the flow is divided into two paths, one through the sensor tube/capillary and the other through the line containing LFE.
3. **Flow body:** The meter size is determined depending on the meter capacity. These are available in widths from 25 to 75 mm with lengths ranging up to 250 mm to cover various flow categories (low/medium/high). The flow body has inlet and outlet flow tubes with suitable fittings to house the flow conditioning section like LFE. Major parts are as shown in Fig. VI/4.1.0-2, there will be a sensor tube, the bypass including LFE as a mechanical part of the meter. In the case of Mass flow controller (MFC) there will also be one integral control valve. The meter/controller in a suitable enclosure of required IP rating is mounted on the top of the flow body. Mostly these are used for low-flow applications with process line size from 6 mm to 25 m. Therefore, most are available compression fittings with suitable O rings. Some of the meters operating at very high flow rates are available in wafer and flange pipe sizes [12]. For *semiconductor* applications materials used should of very high purity and the surfaces of wetted parts must be very polished without any sharp edges. Instruments should have extremely low leak rates; and internal flow paths must have no sharp corners, cavities, or dead spaces where particles can collect [12].
4. **Bypass:** Straight tube designs with full (laminar) low flow through the sensor tube are possible as already discussed during the initial discussions of this section, yet most manufacturers go for a bypass design to accommodate higher flow rates. In order to establish the flow through the capillary sensor tube, it is necessary for a proper bypass with a fully developed laminar flow in its passages. There are a number of possible designs for laminar flow elements (LFEs). These are a set of tube bundles, single capillary design, slotted or annular passage with 90 degrees turn [12], honey comb design, to name a few. A typical design is shown in Fig. VI/4.0.0-2 (lower RHS part).
5. **Sensor tube:** The sensor tube could be conceived of as the heart of measurement. Here the measurement of the mass flow rate passing through it is done to infer the total flow rate passing through the entire flow meter. As already explained in Subsection 4.0.1.2, there are two types of capillary sensor tubes: straight and U shaped. The sensor tube has the following requirements. *Length: diameter ratio 100:1; velocity is in the range of 5–10 m/s, Reynolds number* < 100, *and mach number* < 0.05 [12].
   - *Straight tube:* Straight tube designs offer stress-free conditions and are used in applications for fluids which are not totally clean and require smaller pressure drop. Also, it facilitates cleaning. Straight tube designs normally have larger diameters.
   - *U tube:* In contrast to straight tubes, U tube designs are very compact having a total length ranging from 10 to 100 mm [12]. Compared to straight tube designs, U tube designs have relatively small internal diameter and wall thickness. The ends of the "U"-shaped sensor tube are embedded in a metal block of high thermal conductivity so that it can act as a thermal bus and both ends have the same temperature [12].

The sensor tube is put in an isothermal shell air. This type of design is suitable only for very clean fluid; to ensure the cleanliness of fluid, particulate filters are installed upstream as already discussed.

6. **PRTDs:** There are two RTDs (self-heated). The two adjacent PRTD windings are identical and located symmetrically on two sides of the sensor tube symmetrical about the center of the sensor tube length as shown in Fig. VI/4.0.0-2. Together, they cover only a fraction of the total length of the sensor tube. The windings have electrical isolation from sensor tube by insulating coating. These are wound over the capillary tube externally and are bonded with a stable bonding compound. Capillary mass flow has high accuracy specifications and uses high-purity platinum fine wire. As indicated during the initial discussions, some use three RTD windings. Central winding is self-heated. The other two windings are used for temperature measurement only. Another point to be noted is that since T_1 in this case is measuring fluid temperature and is not self-heated it would remain *constant* (if no change in process fluid temperature) and the changing nature of T_1 shown in Fig. VI/4.1.0-1B will not be applicable, instead it will be *parallel* to the x axis.
7. **TMFM and TMFC electronics:** Basically the electronics of TMFM consists of a bridge circuit comprising a number of resistances in various arms. These resistances take care of the cable resistance and compensations. Two PRTDs are connected to two diving arms of the bridge. Like any other bridge circuit the power supply is connected to two opposite corners of the bridge and the output change in voltage is sensed from the other two corners. The output after signal processing and (DSP as the case may be) is taken as the meter output which could be of a variety of types including analog 4–20 mADC, HART output, fieldbus, digital, etc. In the case of TMFC output of TMFM electronics is connected to a controller which also includes a set point (not shown—and could be integral also), to generate the necessary output to regulate the integral control valve of the meter as shown in the RHS part of Fig. VI/4.1.0-2.
8. **Flow control valve:** These valves are an integral part of the flow meter. These are similar to a solenoid valve, i.e., they have an electrical armature and solenoid (acting as a magnetic field) for its operation. Although the valve has a solenoid it acts like a linear electric motor with a coil/armature combination for smooth operation. These valves can be modulated by regulating the magnetic field, i.e., by solenoid current. The valve also offers good shut off condition, for ensuring leak-proof conditions a metal seating may be used. By changing the valve configuration the valves can be made fail to close (FC) or fail to open (FO). Usually fail to close types are used. For details about FC/FO Chapter VI of Ref. [13] may be referred to. The valves normally offer very good speed of response.
9. **Materials of construction:** Typical materials of construction of capillary TMFM are as follows:
   - *Body:* 316 SS or aluminum/plastic for making the body lightweight and low cost;
   - *Wetted parts:* 316 L stainless steel including control valve body; sensor tube may use corrosion-resistant alloys also;
   - *Control valve plug:* Fluorocarbon and other corrosion-resistant materials;
   - *"O" rings and valve seats:* Kalrez for valve seat/Fluoroelastomers or other advanced Elastomer [12];
   - *Sealing:* Elastomeric seals, in some cases metal sealing also.

4.1.3 OPERATING CONDITIONS AND PERFORMANCES OF THERMAL MASS FLOW METERS

In this section conditions under which the meter operates and instrument rangeability and performance will be briefly discussed.

1. **Operating temperature and pressure:** From an operation point of view it has been found that for the majority of applications the temperature range shall cover 10−80°C. Typical ambient temperature for the meter is in the range of −20 to 50°C. The operating pressure for the meter covers a wide range, as high as 350 barg to a high vacuum and as low as 0.05 bar(A). However, the majority of application operating pressures are to the tune of about 35 barg [12].
2. **Flow range:** This type of flow meter can measure gas flow as low as 0.1 sccm (Standard cubic centimeter per minute) and the lowest range could be as low 0−1 sccm. On the maximum side the gas flow ranges flow range from about 0 to ∼1700 slpm (standard liters per minute). Normally the flow meters are categorized in three categories: low, medium, and high flow. In the case of liquid flow, ranges between 0−2 and 0−20 kg/h are available with straight tube designs, e.g., L30 digital LIQUI-FLOWTM Mass Flow Meter. Although a higher flow range would be more cost effective, in such cases other types of thermal flow meter would be preferred.
3. **Performance data:** The following are typical performance data for these meters:
   - *Overall accuracy:* Typical overall accuracy for general purpose applications is about 1% FSD. In the case of semiconductor applications better accuracies are also available. In contrast, for low-cost meters an accuracy of about 2%−3% FSD is also available.
   - *Repeatability:* Typical repeatability of a flow meter is around 0.2% AR.
   - *Typical rangeability or turndown:* Turndown typically is 20:1−50:1.
   - *Response time:* 0.3 s to reach 37% of final value of step input.

4.1.4 DIGITAL THERMAL MASS FLOW METERS

With the introduction of on-chip sensors and other digital electronics supports, application-based digital flow meters in this category of meter are gaining popularity in a variety of applications. A digital flow-metering system normally has embedded electronics covering general functions and specific functions to cater to the requirements of the flow meters, such as multigas/multirange functionality, high accuracy, faster response, and other performance requirements for process control applications and necessary flexibility to meet customer requirements. These meters support high pressure (nearly up to 400 bar) with very low leakage design. These instruments have almost zero pressure and temperature sensitivity. Also, these metering systems support controllers (to implement customer control algorithms) and integral proportional electromagnetic control valves with extremely fast and smooth control characteristics. Major advantageous issues associated with digital meters lie with their digital signal processing and communication capabilities. Normally they support standard RS 232 output interface DeviceNet, Modbus, fieldbus like Profibus, foundation fieldbus. In this connection it is worth noting that there are special sensor chips available for thermal and/or differential pressure-sensing flow-metering also. A number of sensors in combinations can also be fabricated. These can be used for flow/pressure sensing also. The fourth-generation silicon sensor chip SF04 (SFM4100/SDP600 series from Sensirion) is an example [14]. Such chips contain not only a thermal mass flow sensor element along with other necessary components like an amplifier, A/D converter, EEPROM memory, and other digital signal-processing circuitries. These meters have wide application areas such as burner control, gas mixing control, semiconductor processing, medical applications (including respiratory care and anesthesia), leakage testing, etc.

4.1.5 GAS CONVERSION AND ALLOWED GASES

It is possible that capillary tube TMFMs and TMFCs be calibrated with a reference gas, e.g., N_2 and then could be used for another gas by utilizing the gas conversion factor. This is extremely advantageous as it allows:

Safer gases for flow calibration;

Multigas functionality discussed for digital flow meters in Section 4.1.4.
Calibration of rare gas [12].
For the same set of RTDs and heating it can be shown that two gases, gas 1 and gas 2, have the same instrument output in the *linear* range. This means that

$$q_{m1} \cdot C_{p1} = q_{m2} \cdot C_{p2} \qquad \text{(VI/4.1.5-1)}$$

where q_{m1}, C_{p1} and q_{m2}, C_{p2} represent mass flow and specific heat of gas 2.

If we introduce density and volume flow at standard conditions represented by suffix "s" and volume flow by "q" (as mentioned earlier low-flow volume at standard condition is easier to handle) Eq. (VI/4.1.5-1) gets modified to

$$q_{s1} \cdot \rho_{s1} \cdot C_{p1} = q_{s2} \cdot \rho_{s2} \cdot C_{p2} \quad \text{or} \quad q_{s2} = k_{12} q_{s1} \qquad \text{(VI/4.1.5-2)}$$

k_{12} represents the gas conversion factor of the meter from gas 1 to gas 2 and k_{12} is given by $(\rho_{s1} \cdot C_{p1})/(\rho_{s2} \cdot C_{p2})$. Now, generalizing the equation one can say that k_{ij} is the gas conversion factor of the meter for converting ith gas to jth gas. Normally gas conversion factors are given relative to a single primary reference gas, usually air or nitrogen. Most of the manufacturers give a list of gas conversion factors for different gases relative to one reference gas, e.g., N_2/air. Also, manufacturers give a list of gases allowed for the manufacturer's meter model.

4.1.6 SPECIFICATION OF THERMAL MASS FLOW METERS

A typical specification for a capillary type thermal mass flow meter has been given in Table VI/4.1.6-1. It is worth noting that as the specification is a general one not all the data will match with any particular instrument chosen. Also, the best possible data from different manufacturers have been pulled together so naturally there will be deviations from an actual instrument. The specification given is just a guide and the reader should specify the required instrument with due modification based on the application at hand.

TABLE VI/4.1.6-1 Specification for Capillary Type TMFM

Sl. No.	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Gas mainly but for liquid also		
2	Design pressure	~30–35 bar normal high pressure also possible especially for digital type it can be up to 400 barg		
3	Design temperature	−10 up to 70–80°C		
4	Temperature/pressure sensitivity	Almost zero		
5	Environmental condition	Refer to Subsection 4.1.3.1		
6	Pipe size and flow range	Sizes 3/6/12/25 mm to cater to various flow ranges in low/medium/high ranges. In low side from 0.01 slpm to nearly 1700 slpm in higher side but in different spans as per manufacturer's standard. Turn down 20:1/50:1		

Continued

TABLE VI/4.1.6-1 Specification for Capillary Type TMFM—cont'd

Sl. No.	Specifying Point	Standard/Available Data	User Spec.	Remarks
7	Leakage test	Leak-proof typical test $<2 \times 10^{-9}$ mbar l/s He*		*[15]
8	Materials of construction	Refer to Subsection 4.1.2.9		
9	Sensing type	PRTDs		
10	Output	4–20 mADC and Smart version: Fieldbus communication (e.g., PROFIBUS/Foundation fieldbus) available. Apart from these there are RS 232 link, and DeviceNet/Modbus protocol supported		Especially for digital flow meters
11	Output function	Electronic totalizer remote communication, control function with integral electromagnetic valve		
12	Enclosure class	NEMA 4X/IP 65		
	Electronics unit	SS different grades		
13	*Connection and Mounting Details*			
14	Process connection and meter type	Mostly with compression type tube fittings but wafer/flange types are available also		
Performance and Other General Details				
15	Response time	0.5–1 s 300 ms also possible		
16	Warm up time	2–30 min based with varying performance available		
17	Filed calibration	Span and zero		
18	Certification	CE and others as per manufacturer		
19	Applications	Semiconductor industries, leakage tests, medical field, process control, vacuum technology, and custom-made applications with sensor chips		
20	Accessories	Flow conditioner, filter integral control valve, and controller		
21	Transmitter	Built in		
22	Allowed gases	Refer to manufacturer's manual		
23	Gas conversion factor K for the meter	Refer to manufacturer's manual		
24	Special feature	If any to specify requirement		

4.1.7 PRESSURE DROP ACROSS METERS

Pressure drop across sensor tube ΔP_{sensor} is given by

$$\Delta P_{sensor} = C \cdot \frac{\mu}{\rho} \cdot q_m \qquad \text{(VI/4.1.7-1)}$$

where C is a constant, and is dependent on tube geometry. μ, ρ represent the dynamic viscosity and density, respectively, of the gas at operating conditions. From Fig. VI/4.1.0-2 it is clear that pressure drop at the bypass and sensor tube must be the same as they meet so, if there N number of sensor tubes in LFE then the drop in the bypass will be

$$\Delta P_{sensor} = (C/N) \cdot \frac{\mu}{\rho} \cdot q_m \qquad \text{(VI/4.1.7-2)}$$

From the two above equations it can be seen that flow in both paths maintains a constant ratio which corroborates Eq. (VI/4.1.1-1).

With this the discussions on capillary type TMFMs and TMFCs come to an end.

4.2.0 Thermal Dispersion Type Mass Flow Meters

The theoretical background for this meter has been detailed in Section 4.0.2; associated terms related to formula derivation have also been covered there, and now it is time to derive the working formula mathematically.

4.2.1 FORMULA DERIVATION FOR THERMAL DISPERSION MASS FLOW METERS

As is clear from the discussion in Subsection 4.0.2.2 thermal dispersion flow sensors consist of two precision platinum RTDs (PRTDs) duly protected by a suitable sheath as shown in Fig. VI/4.2.1-1. On account of the fluid flow the velocity sensor which is kept at higher temperature than the other PRTD, is cooled, as the flowing fluid molecules take heat away from the velocity sensor. Therefore, thermal dispersion mass flow meters measure the heat convectively

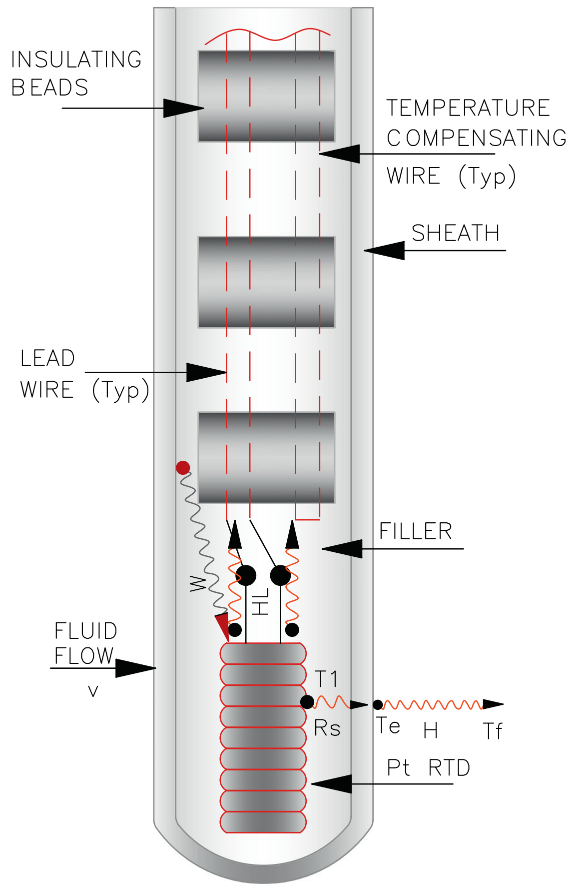

FIGURE VI/4.2.1-1 Energy flow in PRTD of TDMFM.

transferred from the heated velocity sensor—PRTDs to fluid molecules passing through the viscous boundary layer surrounding the sensor's heated surface. The heat transfer is governed by the first law of thermodynamics. The energy flow is also shown in Fig. VI/4.2.1-1. The heater is not shown—for details Fig. VI/4.0.0-3 may be referred to. Under steady-state conditions heat input is in the form of electrical power: (W) = heat output. Heat outputs are in two forms: heat transfer by convection (H_c) and heat loss due to heat conduction through steam of PTRD as shown in Fig. VI/4.2.1-1.

Prior to derivation it is better to clear the legends of various symbols used in the formula. The legends of symbols used have been given in Table VI/4.2.1-1.

TABLE VI/4.2.1-1 Legends of Symbols Used in Formulas for TDMFM

Sl. No.	Symbols	Represents Physical Parameter
1	ΔT	Temperature difference $\Delta T = T_1 - T_f$
2	A_e	External surface area of heated portion $= \pi DL$
3	D	Outside diameter of velocity sensor with sheath
4	h	Film coefficient of convective heat transfer of velocity sensor
5	H_c	Heat convected away from velocity sensor
6	h_e	Equivalent film coefficient of convective given by $h/(1 + h \cdot A_e \cdot R_s)$
7	H_L	Heat loss due to heat conduction through stem
8	I	Current to electrical resistance for heating T_1 (velocity sensor) RTD
9	L	Length of heated portion of velocity sensor
10	R	Resistance of T_1 (velocity sensor) RTD
11	R_1	Electrical resistance for heating T_1 RTD
12	R_s	Skin resistance
13	T_1	Average temperature of velocity sensor (T_1) over heated section
14	T_f	Temperature of flowing fluid
15	W	Electrical power input $= I^2R$

The formula is derived by applying the first law of thermodynamics, to equate energy flow at steady-state condition we get,

$$W = H_c + H_L \qquad \text{(VI/4.2.1-1)}$$

here, unless there is extremely high-temperature gas flow, any heat loss due to radiation may be neglected as it is too small. With long sensor stingers, the end loss (**H_L**) is small [10]. Thus, heat input is virtually equal to the heat output mainly by convection to the flowing fluid. Therefore, with reference to Table VI/4.2.1-1 one can derive:

$$H_c = h_e \cdot A_e \cdot (T_1 - T_f) \qquad \text{(VI/4.2.1-2)}$$

For expression of h_e, serial no. 6 of Table VI/4.2.1-1 and for A_e serial no. 2 of Table VI/4.2.1-1 may be referenced, respectively.

Thus ignoring HL we get finally

$$W = h_e \cdot A_e \cdot (T_1 - T_f) + H_L \text{ or } W = h_e \cdot A_e \cdot \Delta T \qquad \text{(VI/4.2.1-3)}$$

In order to calculate H_c, we must solve Eq. (VI/4.2.1-3). The film coefficient, h (hence h_e), in Eq. (VI/4.2.1-3) is better discovered by solving empirical correlations (as there are a number of factors and issues discussed in Subsection 4.0.2.1 to be taken care of). Thus after solving h_e, we have to keep either ΔT or W fixed and use the other to find the mass flow. Thus this gives rise to two measurement method types already discussed in Subsection 4.0.2.2, there will be two modes of operations (also subsection 4.2.1.4 may be referenced for details):

- Constant power (current) mode with ΔT as measuring output;
- Constant temperature differential with W as measuring output.

Our main aim is to find q_m, so we have to find the ways and means for two modes discussed.

1. **Constant ΔT:** One can measure the electrical power in watts supplied to the heated velocity

sensor and relate this to the heat transfer due to natural and forced convection via Eq. (VI/4.2.1-1): $W = H_c + H_L$.

2. **Constant power:** One can compute the temperature differential ΔT and the heat lost via natural and forced convection with $W = h_e \cdot A_e \cdot \Delta T$ via Eq. (VI/4.2.1-3). However, it is necessary to solve for h or h_e.
3. **Calibration curve:** From the above it is also clear that Eq. (VI/4.2.1-1) through Eq. (VI/4.2.1-3), can be solved for a constant h/h_e (which is dependent on a number of other factors discussed later), by calibrating with the actual gas, under operating conditions in a pipe. This means it is possible to derive a calibration curve relating the power input to the sensor W to the mass velocity/flow, as long as the *film coefficient **h** does not change* with time (due to sensor degradation) [10]. Now we have to look into the issues and various terms which affect h/h_e.

   Let us now address various factors and issues which can cause heat loss and can enable us to empirically solve h/h_e.
4. **Factor/loss in heat flow:** There are a number of factors which result in heat loss.
   - *Conduction loss:* There would be some heat loss through the stem of the velocity sensor in the form of heat conduction. This has been denoted as H_L in Eq. VI/4.2.1-1. This is an unwanted heat loss and needs to be taken care of.
   - *Skin resistance loss:* With reference to Fig. VI/4.2.1-1 it can be seen that if the actual temperature sensed by PRTD is T_1, then the effective average surface temperature T_e over the length (L) of heated surface is reduced and T_e is less than T_1. Since there is less temperature it means there is some heat loss. This is, heat H is passed through the filler and sensor sheath. The resistance offered by them is the skin resistance (R_s) and is established by

$$\text{Heat } H = R_s \cdot (T_1 - T_e) \qquad \text{(VI/4.2.1-4)}$$

5. **Heat transfer coefficient (h) issues:** From the previous discussions it has been seen that we need to find the solution for h/h_e. In this subsection brief discussions on the same will be established. However, it is better prior to going for actual discussions, for the reader to become familiarized with various terms explained in Subsection 4.0.2.1.

   In order to establish film coefficient h it is necessary to understand the empirical correlation. From Subsection 4.0.2.1 we have seen there is a nondimensional parameter Nusselt number (Nu) which is related to h.

$$Nu = hL/\lambda \qquad \text{(VI/4.2.1-5)}$$

where, as mentioned, L is a representative dimension for the pipe and its outer diameter is D.

Also, Nu = function (R_e, P_r, Gr, M, Kn).

Reynolds number (already detailed in Section 1.1.2 of Chapter I) $R_e = \rho \cdot v \cdot D/\mu$ where ρ = density at operating condition, v is the average velocity, and μ is the absolute viscosity of fluid.

Prandtl number, $P_r = \mu C_p/\lambda$; where, μ = absolute; λ = thermal conductivity; C_p = specific heat.

Grashof number (Gr) $= Gr = \frac{\text{Buoyancy force}}{\text{Viscous force}}$. The other two dimensionless parameters are the mach number and Knudsen number, already explained in Subsection 4.0.2.1. For simplifying and solving h one can make legitimate assumptions such as:

- Natural convection is embodied in R_e and P_r;
- The fluid velocity is much less than the speed of sound (1/3 speed of sound) so, subsonic; $M < 1$; hence density is relatively *constant*;
- The flow is not in a high vacuum, so the effects of Gr, M, and Kn, can be ignored.

Therefore, Nu is a function of R_e and P_r. The generalized correlation of these factors can be:

$$Nu = A + B(P_r)^C \cdot (R_e)^n \qquad \text{(VI/4.2.1-6)}$$

where, A, B, C, and n are referred to as gas factor, hence calibration, constants. These constants also account for deviations from an ideal condition and for end conduction and skin resistance. Prandtl number, $P_r(P_r = \mu \cdot C_p/\lambda)$, as is seen from the formula in brackets, is determined by the properties of the gas under calibration, and the Reynolds number, R_e, as already established in Chapter I, is governed by the fluid mass velocity, i.e., ρv, the viscosity μ and the geometry of the pipe. Thus from these issues h can be determined from gas properties.

6. **Conservation of mass and conduit factor:** Since mass is an intrinsic property of fluid so, one can write

$$q_m = \rho_{op} \cdot v_{avgop} \cdot A_{pipe} = \rho_b \cdot v_{avgb} \cdot A_{pipe}$$

where ρ represents density, v_{avg} is average velocity, and A_{pipe} is the area in the pipe. The operating condition and base conditions have been differentiated by op and b as the respective suffixes. The flow is measured by one point velocity, hence a factor referred to as conduit factor needs to be taken into account. Conduit factor (F_c) for a point velocity v is given by

$$F_c = v_{avg}/v \qquad \text{(VI/4.2.1-7)}$$

The value of $F_c = 0.5$ for laminar flow ($R_e \leq 2000$) [16] and $F_c = 0.83 \pm 0.03$ for turbulent flow ($R_e > 40{,}000$) [16].

An in-line flow meter with flow conditioner F_c is almost unity. Also, as the insertion flow meter has the center of active area that coincides with the center of pipe, full velocity distribution is seen. Thus, for fully developed flow F_c is near unity. Therefore through conduit factor mass flow can be arrived at, by sensing average velocity. There are alternative approaches for which for further reading [16] may be referenced.

In the above discussions it has been stated that there are two kinds of approaches: constant current/power and constant differential temperature approaches. We now investigate the characteristics of the flow meters for these.

4.2.2 THERMAL DISPERSION MASS FLOW METER CHARACTERISTICS ISSUES

From the above discussions (Subsections 4.2.1.1 and 4.2.2.2) as well as during discussions in Subsection 4.0.2.2 it has been found that there are two approaches for TDMFM. As the majority of industrial thermal mass flow meters are thermal dispersion types, both options are offered by various manufacturers. Apart from these there are a few other characteristics, such as response time, pressure effect, and temperature compensations, etc. that are also important. In this section brief discussions have been presented on these two types, along with a few other characteristics of thermal dispersion type thermal mass flow meters.

1. **Constant differential temperature type:** As the name implies, a constant difference in temperature (ΔT) between the velocity sensor (T_1) and the fluid temperature sensor (T_f), i.e., constant temperature difference between heated velocity sensor and the reference sensor, is maintained. The instrument controls the amount of power to the heater to maintain this temperature difference. In this approach ΔT is set during calibration of the meter. With the changes in flow rate, power (hence current) is regulated to maintain this constant temperature difference (ΔT). As shown in the generic curve of Fig. VI/4.2.2-1A, at very low mass flow there is hardly appreciable heat transfer, naturally there will be not be a greater tendency to create a temperature difference. As a result of this, the amount of electric power needed will be quite low. However, with an increase in mass flow rate, there will be a tendency for change in the difference in temperature set. Therefore, the amount of power required to maintain a constant temperature difference increases. In contrast, if one notices the curve shown, the rate of change of power (i.e., slope) will be highest during low velocities to provide excellent low-flow sensitivity. This is something like the requirement of high acceleration starting moving a car from rest. As the mass flow rate increases,

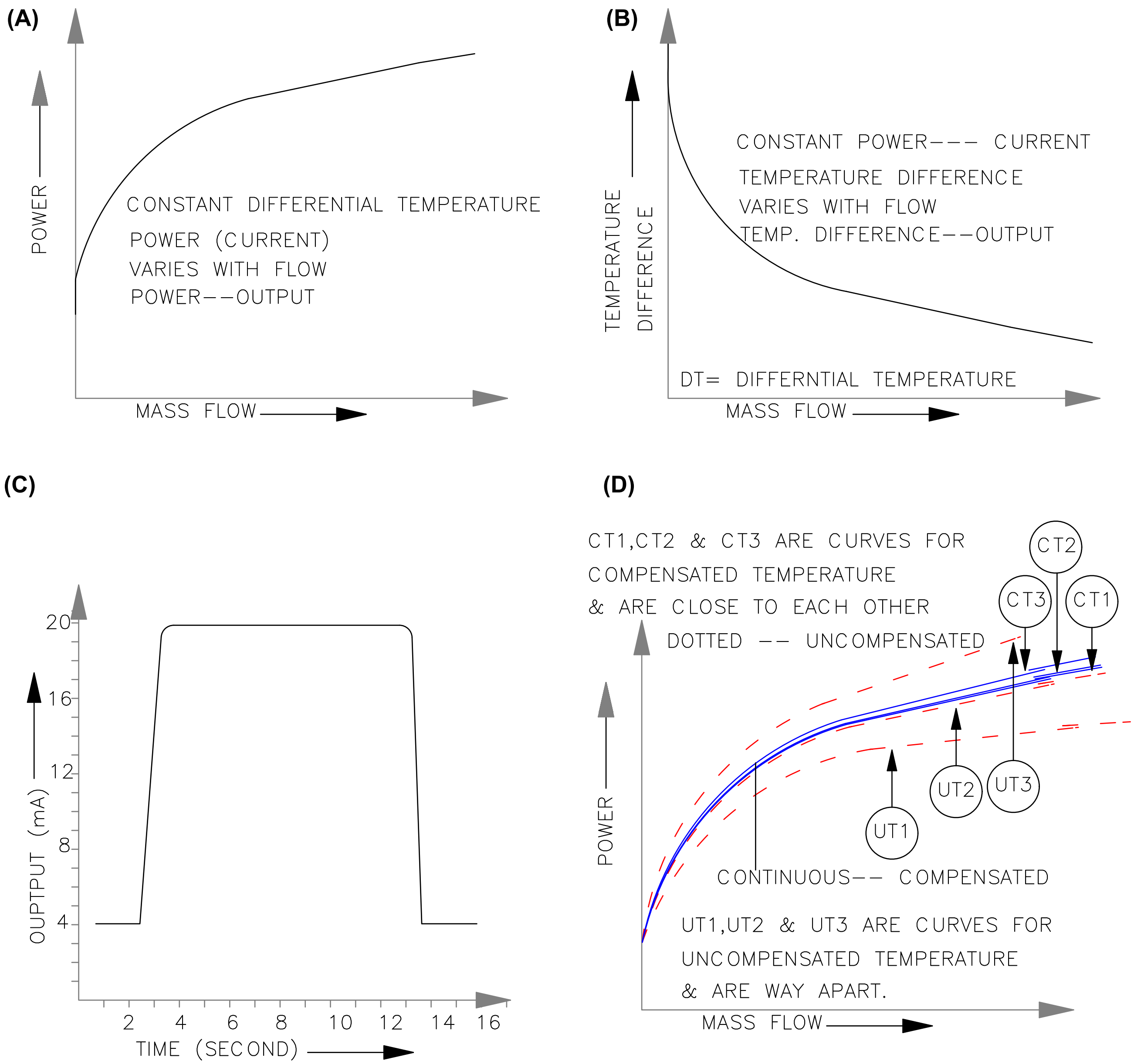

FIGURE VI/4.2.2-1 Characteristic curves for TDMFM. (A) Power versus mass flow. (B) DT versus mass flow. (C) Response time TDMFM. (D) Temperature compensation. *(C) Developed based on Thermatel®, Thermal Dispersion Mass Flow Measurement Handbook, Magnetrol. http://us.magnetrol.com/Literature/1/54-621.4%20Mass%20Flow%20Handbook.pdf; Courtesy of Magnetrol.*

the power increases as shown but the rate (slope) is low. This permits flow measurement at very high flow rates providing high turndown capabilities [17]. As seen from this the relationship is nonlinear and linearization takes place at the transmitter.

2. **Constant power (current) type:** Here the temperature difference (ΔT) between the heated velocity sensor and the reference sensor measuring the process temperature, is used as the output to measure mass flow in the pipe. The temperature difference (ΔT) decreases

with an increase of mass flow rate in a nonlinear way, as shown in Fig. VI/4.2.2-1B. At low mass flow rates the temperature difference between the sensors referred to above is greatest, as a lesser amount of heat is convected to the fluid flow. When the mass flow rate increases, on account of heat convection, the temperature difference (ΔT) decreases, as shown in Fig. VI/4.2.2-1B. As is clear from the figure under reference, the rate of change in ΔT with mass flow rate is very large at the low flow rates. This provides very good low-flow sensitivity. With an increase in flow rate, the temperature difference decreases with lower (slope) rate of change. The meter also shows good flow sensitivity at higher flow, also giving good turndown capabilities. From the above discussions it is clear that in both the cases there are nonlinear characteristics. Such nonlinear characteristics are linearized in transmitters discussed later.

3. **Response time:** Response time is an important characteristic. There will be some delay in response, because there will be some thermal mass which has to heat up or cool down, before the instrument can response. In the case of TDMFM, constant power type is a passive operation. The temperature difference depends on how long it takes for the heated velocity sensor to get heated up or cooled down with a change in flow. The response time is measured by a step change, and it is measured by the time the instrument reaches 63% of the final value, i.e., time constant. Therefore, it depends upon the amount of step change and the type of gas. In the case of a constant temperature difference operation, the power is needed to be changed which is faster than that for making such a change for temperature difference to maintain constant power. In the case of constant temperature difference, the power to the heater is controlled to maintain a constant temperature difference. Therefore, the constant temperature difference type always has a better response time than the other type. Some manufacturers use a PID control circuit, e.g., TA2 type of Magnetrol [17]. The typical response time for a constant temperature difference has been depicted in Fig. VI/4.2.2-1C developed based on Ref. [17]. The typical response time for a constant differential temperature type is <10 s (1−8 s), while for a constant power mode it is in the region of 15 s as it has to make the change of temperature to the entire mass. The higher the flow, the faster will be the response time.
4. **Temperature compensation:** From the discussions so far it is clear that heat convection from the velocity sensor depends on properties of the fluid, especially for a gas. There are some properties of fluids (especially gas) that depend on the temperature. Thus the heat convection from the sensor is affected whenever there is a change in fluid temperature. Therefore, it is necessary that a suitable arrangement should be made to give the temperature compensation. In TDMFM there are two sensors, a velocity sensor and a temperature sensor, and both are put into the ratio arms of a Wheatstone bridge, therefore temperature compensation is taken care of. This takes care of the change in temperature. However, it may not take care of the effect of properties of fluid, which are changed due to the temperature change. Therefore some manufacturers, e.g., Magnetrol, use a real-time temperature compensation method. Here the temperature of the fluid is measured and the mass flow computation at the transmitter is automatically compensated based on the temperature variations. This method of compensation prevents degradation of accuracy due to changes in fluid temperature which may change the heat convection. Fig. VI/4.2.2-1D shows two sets of curves: (red) a dotted curve to represent the uncompensated flow curve and a (blue) continuous curve to represent the compensated curve. Comparing the two curves one can see that in the case of uncompensated curves with

change of temperature curves separate from one another. Meanwhile in the case of compensated curves these are more or less close to one another. According to Magnetrol "If the instrument does not provide a temperature measurement, the instrument cannot provide real time temperature compensation. This is especially a consideration with other manufacturers' constant temperature difference operation; these designs have a reference RTD and a self heated RTD. The reference RTD is used in the electronic circuit and does not provide temperature measurement. Thus these instruments do not provide real time temperature compensation" [17−p17]. It is also a fact that resistance of self-heated RTD also changes, so that without the knowledge of such a change the temperature compensation will be incomplete.

5. **Pressure effect:** Pressure changes in the case of gas, change the density of the gas and so will also have an effect on the heat transfer rate discussed in section 4.2.1 (see eq. VI/4.2.1-6).

With this we limit our discussions on characteristic issues pertinent to TDMFM to give a detailed account of the meter.

4.2.3 DESCRIPTION OF THERMAL DISPERSION MASS FLOW METERS

(*Various data indicated here are from the technical brochures of reputed manufacturers so as to give a feel to the readers of the real-life data. Amongst the available data from various manufacturers, the best or highest values or better materials have been indicated. Based on the application and budget, the designer needs to choose suitable data from the manufacturers' catalog.*)

1. **General description:** In this section short descriptions of TDMFM will be given, along with various versions of the metering systems that are on offer to users.

   A thermal dispersion mass flow-metering system basically consists of sensors and a transmitter, which can be of two types or versions:

- *Integral or compact version:* Sensors and transmitter as a single mechanical unit.
- *Remote version:* Sensors mounted in the pipeline while it is mounted at another place physically separate from the sensor.

  Normally the following parameters are measured through this type of flow-metering system:

- Fluid mass flow;
- Fluid temperature;
- Fluid heat flow.

It is interesting to note that TDMFM is best suited for gas flow measurement, especially for low flow range at low to medium pressure (for meter sensitivity). However, this type of meter can also be used for liquid services in some special applications. So, instead of gas mostly referred to in various documents, "fluid" has been used here. *Why is it not suitable for liquid?* On account of the following reasons, TDMFMs find very limited applications in liquid flow measurements:

- Thermal conductivity of liquid is high, so it can take away a major portion of the heat at zero flow conditions and naturally sensitivity suffers;
- In the case of liquid there will be the probability of cavitations (especially liquids with lower vaporization point). Therefore, large ΔT cannot be used. This too will reduce meter sensitivity and the meter has to depend on low ΔT for its operation.

  From a meter-mounting point of view there are two versions available for the metering systems. These are the in-line and insertion versions as shown in Fig. VI/4.0.0-3.

- *In-line version:* In this version two sensor probes with a flow body are permanently fitted into the pipe/tube of different sizes (6−300 mm) by threaded or flange process connections.
- *Insertion type probe:* Here the flow-metering probe, comprising of two sensors,

is inserted through a sealed compression fitting or flanged stub into the pipe or duct. This is suitable for measuring gas velocity from 0.5 to 150 nm/s [18]. Usually insertion types are applied for large-diameter pipes such as > 75 mm up to 5 m. The insertion type probe measures the flow at the point where it is inserted. Therefore, the measured flow is affected by the flow profile at the location of the sensor. It is desirable to locate the probe where it can sense average velocity. For turbulent flow, based on Reynolds number, the location of the average velocity will lie in the range between *0.07 D and 0.13 D*. It is very difficult to locate the exact point of average velocity, which also changes with Reynolds number. Also, the velocity profile at this point is very sensitive [17]. Another fact is that the velocity at the center of pipe is normally nearly ***20%*** higher than the theoretical average velocity. Therefore, it would be best to locate the sensor at the centerline of the pipe. Knowing the pipe ID it is not difficult to locate the sensor at the center. Then, for average velocity a known factor (20%) can be adjusted for at the meter electronics. So, the best and simplest way of installing an insertion type sensor would be to locate it at the center of the pipe. This also helps in determining the length of the probe easily.

Also, there is a division in sensor design also, these are:

- Two-temperature design;
- Four-temperature design.

In the case of a traditional sensor design there are two sensors: the velocity sensor (T_1) and the fluid temperature sensor (T_f). There are designed to minimize errors in measurements and temperature compensation. Each of the above two sensors has another additional senor, designated as (T_{1C}) and (T_{fC})s as shown in Fig. VI/4.2.3-1. Details on these are given in the next section.

Now let us see various other details, such as input/output, operating conditions, flow range

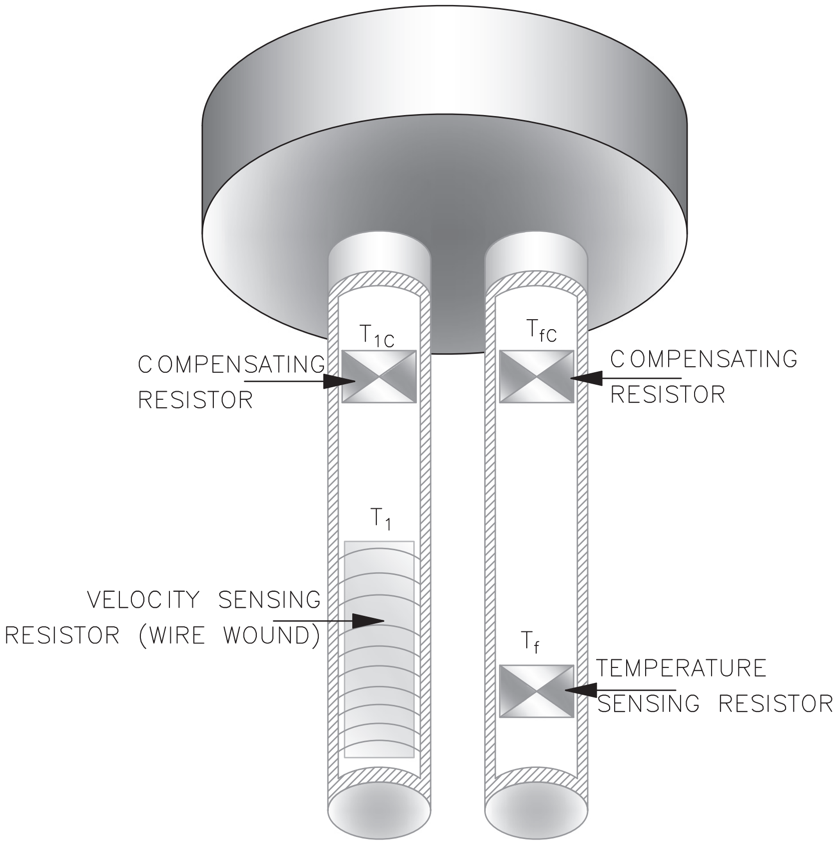

FIGURE VI/4.2.3-1 Four-temperature sensor for TDMFM.

performance details, and materials of construction, etc. Sensors and transmitter design details have been discussed in Section 4.2.4.

2. **Input to the meter:** The major inputs are process parameters discussed in the initial part of this section. In addition to these there will be a number of other inputs normally accommodated in the meter, including auxiliary inputs for HART protocol, fieldbus, and for links like RS 485 with MODBUS. These auxiliary inputs are configurable for gas group, totalizer reset, positive zero return, start zero point adjustment, error message reset, zero point adjustment start, etc. [19]. In addition to these there are provisions for auxiliary analog and digital inputs, and also for interlock and control purposes also.
3. **Output:** There are many types of output available in modern digital meters. Some of these are listed here:
   - *Conventional output:* conventional 4−20 mADC or superimposed active 4−20 mADC with HART and pulse output system alarms, process alarm through potential free contact;
   - *Digital communication:* Foundation/ Profibus fieldbus, HART protocol, and also digital link RS 485 with MODBUS protocol.
4. **Process conditions:** The following are a few relevant parameters for process conditions:
   - *Pressure range:* Normal pressure is around >40 barg. Pressure ratings for flanges are normally PN 16 (ANSI 150 lb class) for pressure range 0−20 barg and pressure ratings for flanges are normally PN 40 (ANSI 300 lb class) for pressure range 0−40 barg.
   - *Process temperature:* Meters are available in the ranges −40 to +100°C and −40 to 175°C or −25 to 300°C (e.g., ABB Sensyflow).
   - *Flow range:* Flow ranges are specified based on sizes in Table VI/4.2.3-1.
   - *Gas compositions:* There are two classes, such as pure gases like N_2, O_2, CH_4, etc. and the other class is a mixture of gases such as air, natural gas, combustion gases, flare gas, stack gases, etc.
5. **Environmental conditions:** A few environmental conditions are as follows:
   - *Ambient temperature:* −40 to 60°C (highest range noted from literature); storage: −40 to 80°C;
   - *Humidity:* 90% RH;
   - *Enclosure class:* IP66/67.
6. **Materials of construction:** Stainless steel and ceramic sensors are standard. Material details normally found are as listed here:
   - *Transducer element:* Stainless steel 316L, C22 alloy, A249;
   - *Transducer body:* 1.4404 to EN10272 and 316L to A479 [19];
   - *Protection guard:* Stainless steel 316L, A666;
   - *O ring seal:* EPDM, Kalrez 6375, Viton FKM (Refer Fig. VI/4.2.3-2 for details on various seals mentioned);
   - *Bushing:* PEEK GF30, PVDF.
7. **Performance parameters:** The following are major performance parameters of available meters:
   - *Overall accuracy:* Standard: ±2% AR; variation with flow range: 1.5% AR, 10%−100% range; 0.15% FSD (0%−10%);
   - *Repeatability:* ±0.1% (ABB) to ±0.5% AR;
   - *Response time (63% of final value of step):* 1−7 s for constant ΔT; ~10 s for constant power. However, up to 2 s is possible;
   - *Turndown:* 150:1;
   - Calibration accredited to ISO/IEC 17025(E + H).

TABLE VI/4.2.3-1 Flow Range for TDMFM

Line Size	Type	Mass Flow (kg/h)		Volume Flow nm^3/h	
		Minimum	Maximum	Minimum	Maximum
15	In-line	0.5	53	0.38	41
25	In-line	2	200	1.5	155
50	In-line	10	910	7.5	704
80	In-line	20	2030	15.5	1570
80	Insertion	20	2030	15.5	1570
100	In-line	38	3750	29	2900
100	Insertion	38	3750	29	2900
200	Insertion	80	12,500	62	9666
400	Insertion	300	50,000	232	38,670
600	Insertion	700	115,000	540	88,940
1000	Insertion	2000	32,000	1546	247,846
1500	Insertion	2500	72,000	1933	556,844

Courtesy of E + H.

***EPDM** (ethylene propylene diene terpolymer) is synthetic rubber consisting of primarily ethylene and propylene derived from oil and natural gas, with an extremely high durability as roofing membrane.*

*DuPont™ **Kalrez®** perfluoroelastomer parts have been the sealing material of choice for long-term reliable sealing in the harshest chemical environments. Kalrez® Spectrum™ 6375 is designed to give outstanding performance in the widest possible range of chemicals and temperatures.*

***Neoprene/CR:** Neoprene/CR rubbers are homopolymers of chloroprene (chlorobutadiene). It has its use for quite long, may be among the earliest synthetic rubbers used to produce seals. It has good aging characteristics in ozone and weather environments, along with abrasion and flex cracking resistance.*

***Nitrile /NBR** On account of its excellent resistance to petroleum products, and its ability to be compounded for service over a temperature range of –35°C to +120°C (–30°F to +250°F), is the most widely used Elastomer in the seal industry today. **Viton** (FKM) is commonly used in O-rings and many other usage e.g. chemical-resistant gloves. It is a brand of synthetic rubber and fluoropolymer elastomer. Viton fluoroelastomers are categorized under the ASTM D1418 and ISO 1629 designation of FKM.*

FIGURE VI/4.2.3-2 Commonly used sealing materials.

4.2.4 THERMAL DISPERSION MASS FLOW METER DESIGN ISSUES

1. **Sensor design issues:** Normally in the sensing system there are two sensors—a heated velocity sensor and a reference temperature sensor. The velocity sensor and temperature sensor are either wire-wound or thin-film platinum resistance temperature detectors (RTDs) with a thin insulation layer of glass or ceramic. Each sensor has a rugged, sealed, close-ended, metallic tube referred to as the protection sheath to face the harsh environment. The metal tubes have around 3 mm diameter with a length of about 6–8 mm and it is filled with filler material inside, as shown in Fig. VI/4.2.1-1. These protection sheaths are made of suitable corrosion resistance, such as 316 stainless steel, nickel alloy, Inconel, and Hastalloy. Both sensors are mounted side-by-side. There are some alternatives in design and these are listed here:
   - *Velocity sensor heating:* Some manufacturers (e.g., Magnetol) use precision-matched platinum RTDs for temperature measurement. Also, there will be a separate heater as shown in Fig. VI/4.0.0-3B (inset). There will be a mass balancing element used to ensure that both sensors respond the same to changes in temperature. In the other design, (used by some manufacturers – e.g., Sierra) *self-heated* velocity sensors are used. The velocity sensor is a single electrically *self-heated* PRTD located at the tip. Functionally it heats the velocity sensor and measures its own average temperature (T_1). The other senor is a single *nonself-heated* temperature sensor element (T_f) located in its tip to measure the gas temperature. In the latter design the velocity sensor has a lower electrical resistance of about 10–30 Ohms, causing more current for heating effect and temperature-sensing PRTD. A temperature-sensing PRTD has a relatively high electrical resistance in the range of 300–1000 Ohms [20].
   - *Sheath design:* These days, in addition to close-ended shields of traditional design, the shields are available as open-ended shield also to prevent flow over the velocity sensor to be nonuniform and turbulent, which was a problem associated with the closed shield. This has been detailed in Fig. VI/4.0.0-3B, where the shield is shown with a dotted line to indicate both options.
   - *Insertion probe:* Many manufacturers offer an insertion probe with a constant diameter, this causes most flow to go around the probe and a small portion flows axially down the probe. This secondary flow varies with insertion depth causing inaccuracy. Some manufacturers like Sierra offer insertion probes with shoulders, instead of a constant-diameter insertion probe, to avoid secondary flow and get better accuracy. Typical insertion lengths available are from approximately 200–600 mm to cater to the requirements of large pipes.
   - *Four-temperature design and temperature compensation:* The discussion here starts with reference to Fig. VI/4.2.3-1. In four-temperature design, there will be one additional sensor T_{1C} located a short distance from the T_1 element. Similarly, there will be a second T_{fC} element located a short distance from the sensor T_f. Except T_1, all other PRTDs have a higher resistance value of around 500–1000 Ohms. These additional elements, namely, T_{1C} and T_{fC}, are located in velocity and temperature probes, respectively, and are used to compensate for errors due to temperature variations, conduction, etc.
2. **Transmitter:** A typical electronic transmitter as shown in Fig. VI/4.0.0-3 provides the driving energy to the sensors and in turn performs a number of functions receiving inputs from sensors and power (current) inputs. From the above discussions it is clear that the characteristic curve in both cases of constant difference in temperature and constant

power type TDMFM is nonlinear and the linearization takes place at the transmitter. Therefore, the major functions of the transmitter include but are not limited to: transformation of inputs, computation, and production of linear outputs of the primary dependent variable, i.e., mass flow rate q_m, in the case of multivariable versions, the gas temperature T, and heat flow. The transmitter is housed in an enclosure of suitable Ingress protection (IP) rating (and conforming to the relevant international codes for hazardous applications if applicable). There are two versions of transmitter as already discussed, i.e., integral and remote mounting. Normally the transmitter produces a linear 4−20 mADC along with pulse and other digital signals. Most modern transmitters are intelligent transmitters with a built-in electronics comprising processors and other peripherals. With the introduction of embedded electronics it is now possible not only to have an intelligent operator interface with suitable displays and field adjustments but also to establish digital communication to support various digital protocols and fieldbus systems. Some of the major features offered by modern digital transmitters include but are not limited to the following:

- Digital displays in engineering units;
- Intelligent operator interface panel;
- Validation, calibration adjustment;
- Reconfiguration;
- Digital transmission of data through digital link and protocol (RS485—MODBUS);
- Support HART protocol; or
- Establish communication via fieldbus system;
- Extensive diagnostics.

Among the advanced functions of modern digital transmitters are: gas selection from four-temperature flow sensors, correction for changes in gas temperature, gas pressure effect, and outside temperature [20]. Modern intelligent flow meters have the capability to correct and take care of changes in temperature more precisely than those done in older transmitters connected to a Wheatstone bridge.

3. **Metering system electronics:** The electronic circuit associated with the measurement is the bridge circuit shown in Fig. VI/4.2.4-1. There are two set of circuits shown here. Fig. VI/4.2.4-1A is meant for a constant differential temperature type TDMFM. In this circuit both velocity sensors PRTD (T_1 or R_v) and PRTD meant for measurement of gas temperature are in ratio arms of Wheatstone bridge and are able to provide temperature compensation. As discussed earlier in some cases additional temperature-sensing RTDs are used to provide temperature compensation independent of the bridge circuit. The four-temperature configuration discussed above is an example. In four-temperature measurement all the sensors are fed to an intelligent transmitter with a microprocessor to take care of the linearization and compensation issue. Fig. VI/4.2.4-1B shows the circuit for constant power (current mode). This circuit is shown without temperature compensation, which could be done separately. Here only the modification of the bridge circuit is shown, and the rest of the circuit is the same as that in Fig. VI/4.2.4-1A. As this is constant power (current) mode, the current needs to be measured, monitored, and controlled. The system discussed so far is mainly a traditional system. Modern transmitters are intelligent and they support various digital links, and protocols such as HART and fieldbus systems. Fig. VI/4.2.4-2 shows the typical connection for such protocol support and fieldbus supporting system. The reader is advised to note that the type of connections shown in Fig. VI/4.2.4-2A and B are standard connection modes for all transmitters. Although this is shown in connection with TDMFM, for other transmitters these are also applicable. As shown in Fig. VI/4.2.4-2A, in the case of HART protocol there will be superimposed 4−20 mADC for traditional secondary devices. Also, a

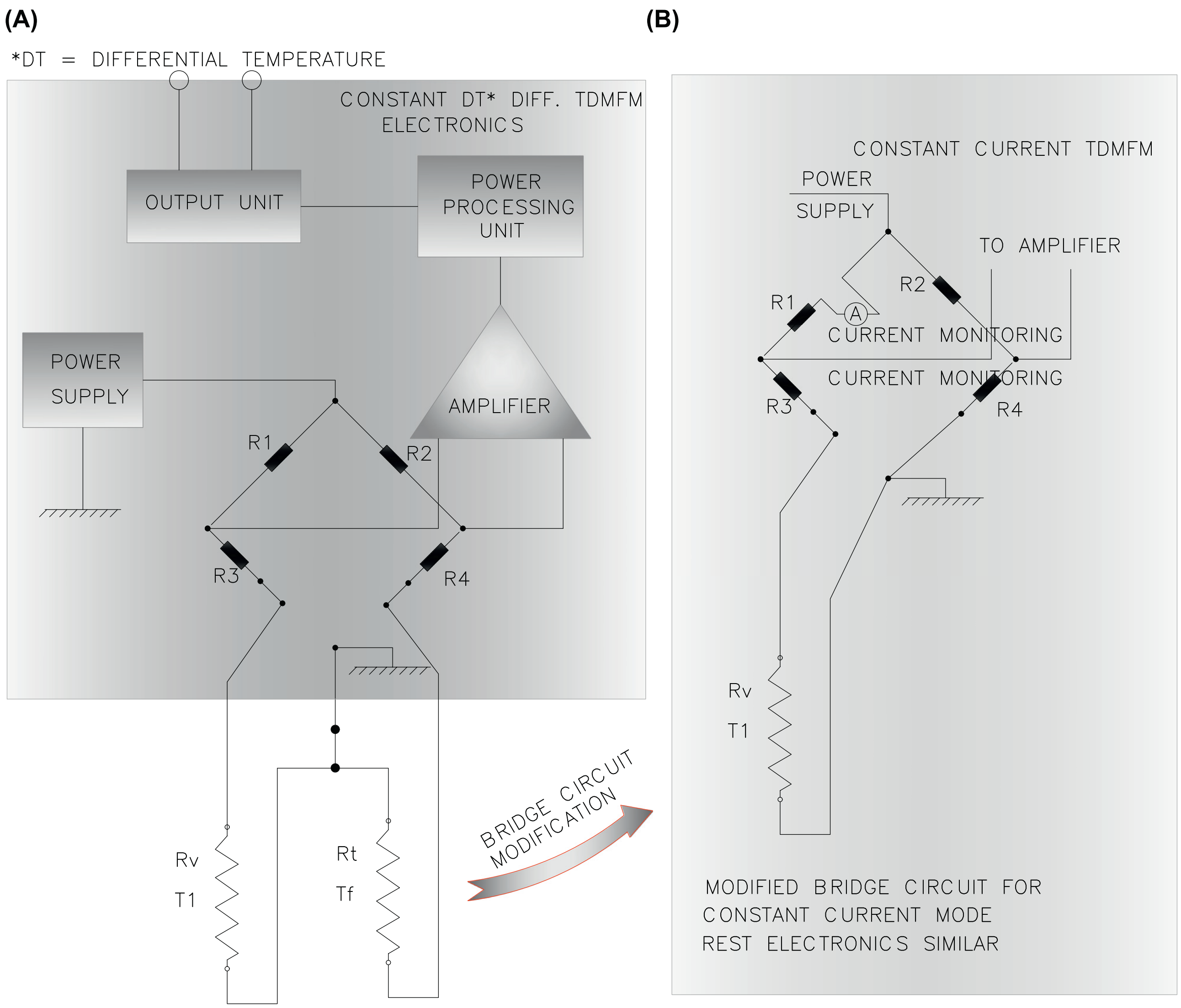

FIGURE VI/4.2.4-1 Bridge connections for sensors in TDMFM. (A) Constant DT* diff. TDMFM. (B) Constant current TDMFM.

configurator can be used for meter calibration and configuration without disturbing the main measurement system. Any PC and/or operator interface can also communicate and exchange data with the help of the frequency shift keying (FSK) modem as HART is based on FSK. For the HART protocol, the author's book [13] may be referenced for details about such transmission and communication.

Fig. VI/4.2.4-2B shows the typical fieldbus connection, where in the same bus a number of transmitters as well as the control system could be connected along with the operator interface as shown. Discussions on fieldbus will be covered later in the book and for further details the author's book [13] may be referenced. In some applications, such as in oil and gas applications, on account of hazardous areas, the system may demand use of barrier and safe fieldbus. In such a case a suitable barrier may be necessary (as shown) for connecting to the fieldbus. Details on safe fieldbus have been discussed in detail in the author's book [7] and may be referenced. In areas which are safe zones, there is no requirement for a barrier and the transmitter with fieldbus

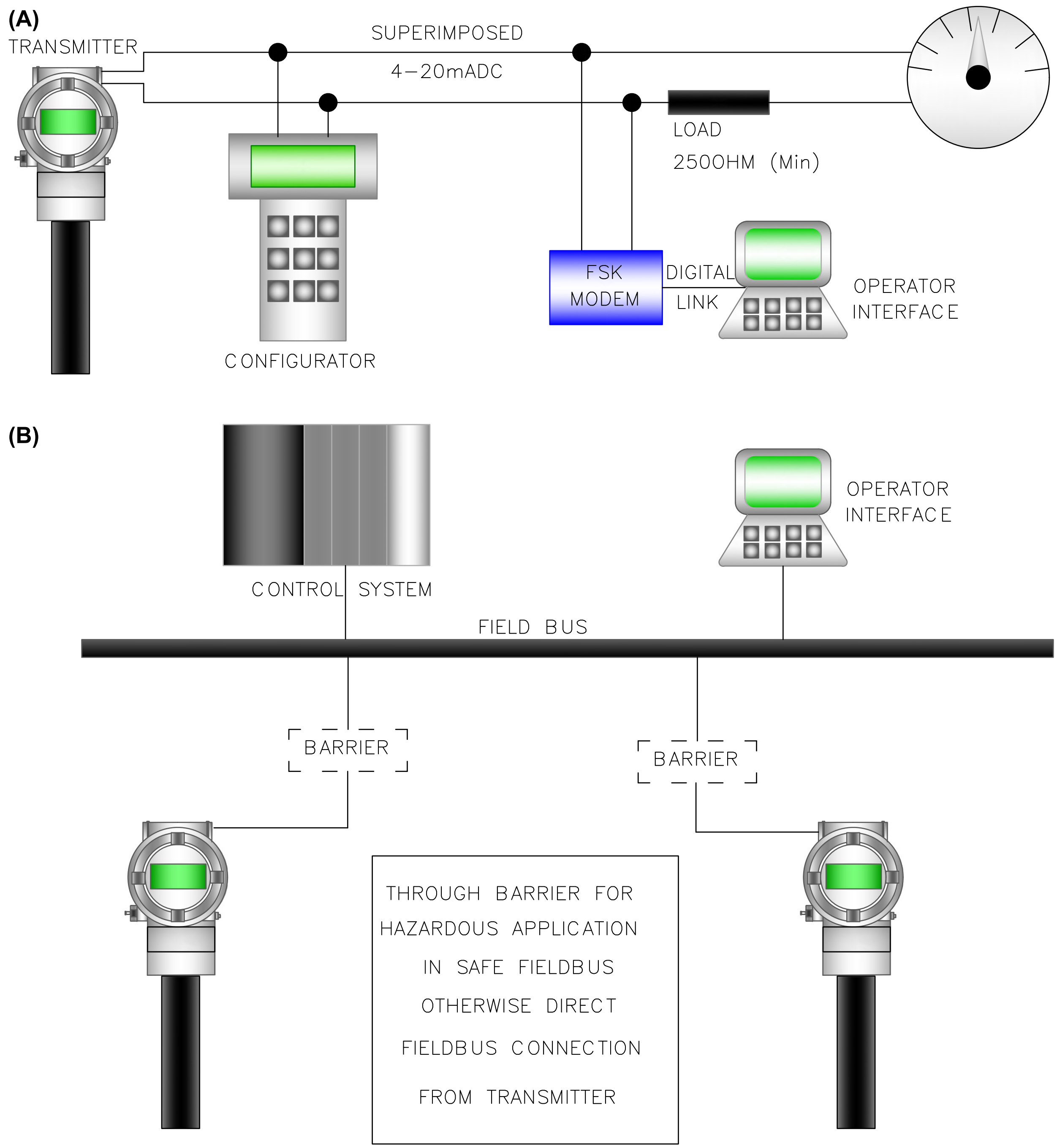

FIGURE VI/4.2.4-2 Intelligent flow metering. (A) Transmitter protocol connection. (B) Transmitter fieldbus connection. *Refer to S. Basu, Plant Hazard Analysis and Safety Instrumentation Systems, Elsevier, IChemE, 2016. http://store.elsevier.com/Plant-Hazard-Analysis-and-Safety-Instrumentation-Systems/Swapan-Basu/isbn-9780128037638/, for details on barrier & safe fieldbus details.*

communication capability can get directly connected to the fieldbus. There are a number of fieldbus systems available, the reader should make sure that the fieldbus systems are supported by the instrument in the question. However, the typical connection styles are the same.

We now look at how the instrument type is specified.

4.2.5 SPECIFICATION OF THERMAL DISPERSION MASS FLOW METERS

A short specification for a thermal dispersion mass flow meter has been given in Table VI/4.2.5-1.

It is worth noting that the data given here are mainly based on data from reputed manufacturers. Also, effort has been made to put the best value or material for any specific aspect. Naturally, data given may not match with any specific manufacturer. Based on the budget and application, readers should specify their requirements to get the optimum results.

TABLE VI/4.2.5-1 Specification for Thermal Dispersion Type Flow Meter

Sl. No.	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Liquid/gas		Mainly gas
2	Design pressure	0–20/0–40 barg		
3	Design temperature	−40 to 175°C even up to 300°C		
4	Environmental condition	Refer to Subsection 4.2.3.5		
5	Pipe size and flow range	Inline flow meters are available from 6 mm* to 100 mm sizes. For insertion type line size could be from 60 to 1500 mm. For typical flow range and meter size refer to Table VI/4.2.3-1		*3 mm also available but rare
6	Insertion length	Insertion type meters are available from 200 mm up to >600 mm		
7	Sensing type	PRTDs of different values in two-temperature or four-temperature mode		
8	Output	Pulse/4–20 mADC Smart version with HART protocol, fieldbus communication (e.g., PROFIBUS/foundation fieldbus) available		
9	Output function	Electronic totalizer, remote transmission, and other control and communications		
10	Materials of construction	Refer to Subsection 4.2.3.6		
11	Enclosure class	NEMA 4X or IP 66/67		
12	Transmitter Material	Powder-coated diecast aluminum, SS different grades		
Connection and Mounting Details				
13	Process connection and meter type	Flange as per EN 1092-1/DIN 2501/DIN 2512N/ANSI B16.5/JIS B2220 Rating ANSI 150 and 300 or PN 16 and PN40 Based on pressure rating. Material SS 316/316L		

Continued

TABLE VI/4.2.5-1 Specification for Thermal Dispersion Type Flow Meter—cont'd

Sl. No.	Specifying Point	Standard/Available Data	User Spec.	Remarks
14	Electrical	½″NPT/G ½″ or M20X1.5 or manufacturer standard		
15	Mounting	Horizontal/vertical/inclined; refer to Table VI/4.2.8-1		
Performance and Other General Details				
16	Accuracy	Refer to Subsection 4.2.3.7		
17	Repeatability	Refer to Subsection 4.2.3.7		
18	Response time	Constant ΔT: 2–7 s and constant power: 7–10 s		Refer to Subsection 4.2.3.7
19	Certification	Necessary certification from appropriate authority for hazardous application and use of barrier as required		
20	Accessories	Meter support (as applicable), flow conditioner, mounting bracket, rate flow and totalizing indicator (local), transmitter, etc. For remote transmitter necessary cable		
21	Hazardous application	Possible with suitable enclosure and certification from a competent authorities for transmitter also. Use of IS barrier		
Transmitter Details				
22	Type	Remote/integral		
23	Load resistance	250 ohm min typical 500 ohm		
24	Display	Mass flow/temperature/volume flow in two/four line backlit LCD/LED display		
25	Operator interface	Interactive push buttons for interaction and quick set up menu. Also possible with configurator as applicable		
26	Power supply	24 VDC with suitable adapter and converter		
27	Input/output	Refer to Subsections 4.2.3.2 and 4.2.3.3		
28	Feature	Four-temperature correction; pressure loss in insertion type and without flow conditioner is negligible. For pressure loss refer to Section 4.2.6 below		
29	Communication	Support fieldbus communication. HART communication		
30	Special feature	If any to specify requirement		

4.2.6 PRESSURE LOSS FOR THERMAL DISPERSION MASS FLOW METERS

In this section short discussions on permanent pressure loss for TDMFM have been presented.

Pressure loss: Pressure loss in TDMFMs is quite low. Frankly speaking, for insertion type meters and in-line meters without a flow conditioner for size up to 80 mm it is negligible (refer to Fig. VI/4.2.6-1). A general equation for pressure loss for a given fluid is given by:

$$\Delta P = k \cdot \frac{qm^2}{\rho} \cdot \frac{1}{D^4} \qquad \text{(VI/4.2.6-1)}$$

where k is a constant and varies with SI and FPS units; it is 1876 (SI units) or 8.4×10^{-7} (US units); q_m is the mass flow rate in kg/h (lb/h); D is pipe diameter in mm (inches); and density is in kg/m^3 (lb/ft^3). However, in most cases, manufacturers supply the data in the form of a logarithmic graphical representation as presented in Fig. VI/4.2.6-1.

4.2.7 BRIEF GUIDELINES FOR THERMAL DISPERSION MASS FLOW METER SELECTION

Brief guidelines for meter selection for TDMF are discussed in this section. These are just

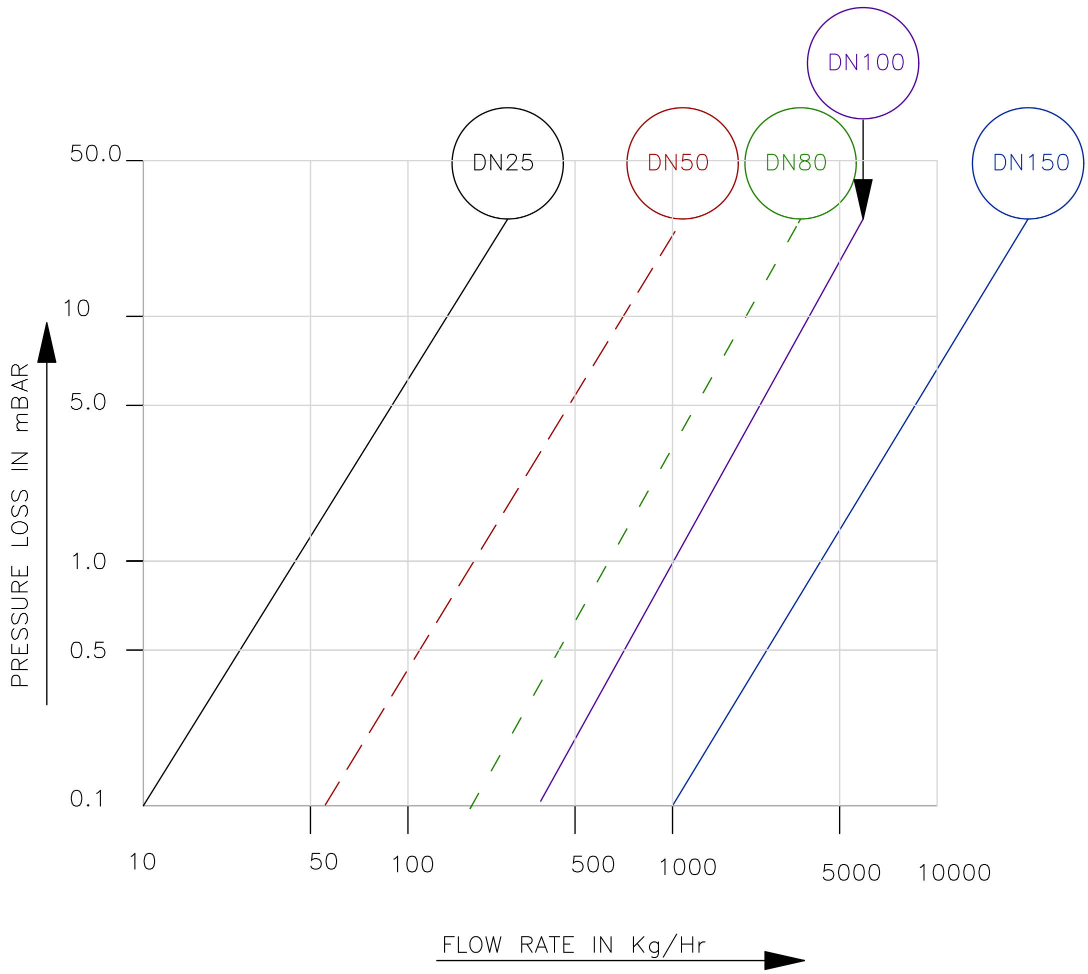

FIGURE VI/4.2.6-1 Pressure loss in TDMFM. *Developed based on Sensyflow FMT500-IG, Thermal Mass Flow meter, ABB limited, Data Sheet 10/14-6.41-EN Rev. H. https://library.e.abb.com/public/a8f1e68709daa767c1257ac30050f4e6/10_14_641_EN_H.pdf. Courtesy of ABB.*

guidelines to help reader concentrate on various points which should be addressed for meter selection and based on the application of relative importance.

1. **Mass flow rate, range and rangeability:** Since this is a mass flow meter, it should be specified in terms of q_m (kg/h in SI). However, in many cases for gas flow it is specified in terms of velocity and volume as discussed earlier. It is necessary to get these figures in ***base condition*** for gases for which the meter is mostly used. The following points may be looked into:
   - *Minimum flow:* This is dictated by detectable base mass velocity. From base velocity one can arrive at the minimum mass flow rate by

   $$q_m = \rho_b \cdot v_{avgb} \cdot A_{pipie} \cdot F_c \qquad \text{(VI/4.2.7-1)}$$

     Eq. (VI/4.2.7-1) has been arrived at by Subsection 4.2.1.6 and Eq. (VI/4.2.1-7). The minimum detectable base mass velocity is nearly 0.1 m/s.
   - *Maximum flow:* The maximum flow is guided by the *Mach number* (which in most cases is subsonic), *flow sensitivity*, and *permanent pressure loss* as discussed above. Based on the mode of operation, flow sensitivity could be found from Fig. VI/4.2.2-1A and B. Based on the minimum and maximum flow achievable one has to look into the rangeability offered by the manufacturer. Typically rangeabilities of 10:1–100:1 are not uncommon. In some cases, rangeability of 150:1 is possible. However, in doing all the exercise one must look for accuracy achievable from the selected meter. In return for high turndown there may be a deterioration of accuracy.
2. **Operating conditions:** Operating conditions mainly include pressure, temperature, and gas composition allowed in the meter.
   - *Pressure:* The pressure range for in-line as well as insertion type meters is guided by the flange rating offered by the manufacturer. Process connection flange rating limits the allowable pressure in the meter in question.
   - *Temperature:* As already discussed in Subsection 4.2.3.4, the meter should be selected based on its allowable temperature.
3. **Gas composition and quality:** While selecting the meter one has to take into consideration the allowable gas for the meter. Apart from gas composition it is important to give due consideration to gas quality. If there are suspended solids in liquids one has to select the accessories like filter, trap, etc. to remove the impurities. Therefore, accessory selection comes from there. Also, for better flow profile one may have to use a flow conditioner (discussed in Chapter XI).
4. **Liquid applications:** In liquid applications, as mentioned earlier, if there is too much difference in temperature between the sensors there may be flashing of liquid into vapor. For this reason a constant difference temperature mode is preferred so that there is control over ΔT. Also, the differential is restricted with 20–30°C maximum to avoid cavitations.
5. **Performance specification:** Last not the least, the performance details given in Subsection 4.2.3.7 must be taken into consideration. Based on the application and budget the best possible performance specification should be selected.

Having gone over some details about the design and discussions on TDMFM, we now investigate how the meters should be installed and associated requirements.

4.2.8 INSTALLATION AND ADJUSTMENTS FOR THERMAL DISPERSION MASS FLOW METERS

Like many other flow meters in this type, the performance of the flow meter also depends on meter installation, which should take into account the flow conditions, applications, and safety details. In this connection the manufacturer's recommendations cannot be overestimated. The discussions start in this section on general installation guidance, where meter orientations,

straight length requirements, and special installation requirements shall be covered. The discussions shall also include some guidelines for various adjustments.

1. **General guidelines:** The following points may be noted as general guidance for installation:
   - All installations should be done only in no-flow no-power conditions (with the exception of hot tap connections for insertion type TDMFM).
   - Installations shall be strictly in accordance with flow direction as described by the manufacturer. Also, the pressure and temperature ratings for the meter should never be exceeded. Ambient conditions recommended for the meter should also never be exceeded
   - *Other important issues are:* Pipe material (suitability for erosion and corrosion property of fluid medium), connection matching, flange and mating flange rating and standard (matching), material deposits, etc., which must be given due consideration prior to installation.
   - In hazardous area applications, before installation, checking for the enclosure, and barrier (as applicable) is necessary to ensure these are in line with standard followed for the installation and supplied items are in line with the requirements and international standard as specified and/or applicable.
   - Suitable measures to check and confirm that the gasket does not come on the flow line. Both end fittings must be properly connected without any leak. The leakage test should be in line with the manufacturer's recommendations.
   - Electrical wiring parameters, etc., including polarity, must be verified prior to installation and connection.
   - In the case of hazardous areas, if an Intrinsic safe (IS) circuit is used then one must make sure that proper application standard is followed.
   - For an in-line meter suitable shutoff and bypass arrangements are made (similar to those shown in Fig. VI/2.5.0-1A). For an insertion type meter one needs to make sure that there is suitable room available for meter removal, especially for a hot tap arrangement i.e. additional space, so give due consideration to this.
   - Thermal flow meters may operate in pulsation but at lower performance, so avoid installation just after the pump.
   - For gases which are very humid or saturated with water, suitable insulation should be used in the meter body and pipe to avoid water droplets condensing on the measuring sensor.

   It is worth noting that many of these points are common for other flow meters and so should be kept in mind even if these are not stated therein.
2. **Meter orientations:** The following points are important for meter orientations:
   - Correct alignment is maintained;
   - Avoidance of condensation mentioned in Table VI/4.2.8-1;
   - Proper pipe work and installation;
   - Proper support for the meter, especially for heavy meters.

   Several possible orientations of the meters are shown in Fig. VI/4.2.8-1. From the figure it is clear that the meter can be installed in horizontal/vertical and inclined orientations as shown.

   However, for such installations a few conditions apply and these are indicated in Table VI/2.4.8-1.
3. **Good engineering practices:** There are a few issues which should be considered as a part of good engineering practices such as the following:
   - Well preparation, welding, and finishing, including removal of welding wastes;
   - Proper gasket sizing and fitting without bulging;

TABLE VI/4.2.8-1 Orientation Details of TDMFM

	In-line Type Meter Transmitter		Insertion Type Meter Transmitter	
Orientation	**Integral**	**Remote**	**Integral**	**Remote**
Vertical	Recommended; only for saturated/unclean gas up flow preferred to avoid condensation			
Horizontal[a]	Recommended	Recommended	Recommended	Recommended
Inclined	Allowed for damped gases			

[a]*Headdown is possible only in limited situations and for clean/dry gases.*

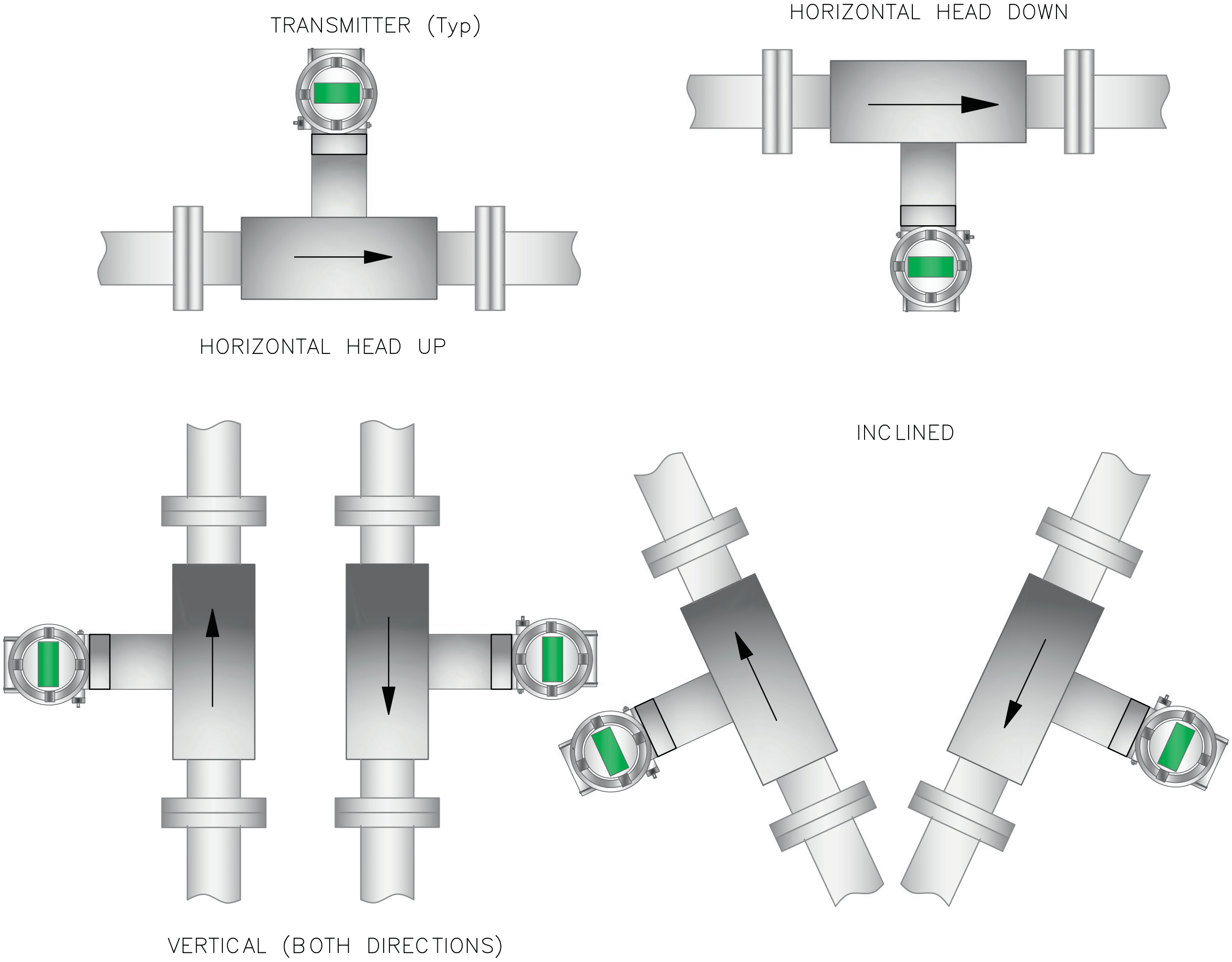

FIGURE VI/4.2.8-1 Orientations of TDMFM.

- Pipe and flange alignments;
- Matching of meter and associated pipe; proper spacing for insertion type meters.

4. **Flow conditioner and tapping points:** Like any other flow meter for TDMFM, flow conditioners are also used to reduce the requirement for straight length. In this connection, Fig. VI/4.2.8-2 may be referenced. This figure also shows the tapping points for pressure measurement. Details on flow conditioner are discussed in Chapter XI.
5. **Straight length requirements:** As indicated earlier, TDMFMs require a good flow profile. Naturally, in order to avoid flow profile disturbances it is necessary to maintain suitable upstream and downstream straight lengths. In this subsection, such requirements are elaborated with the help of Table VI/4.2.8-2.
6. **Adjustments:** After the installation is complete, it is time to check the zero and span for the instrument. It is important to note that for such adjustments the manufacturer's instruction should be followed strictly. In the case of unacceptable zero offset or span deviation, necessary adjustments have to be carried out. For zero adjustments following the manufacturer's procedure, the adjacent shutoff valve should be closed to ensure zero flow. Similarly, when needed, span adjustments can be done following the manufacturer's procedure. High-precision digital meters should be used for electrical span adjustment and calibration verification. Also, it is recommended, as far as possible, that actual process conditions should be maintained for all such adjustments. However, for getting accuracy

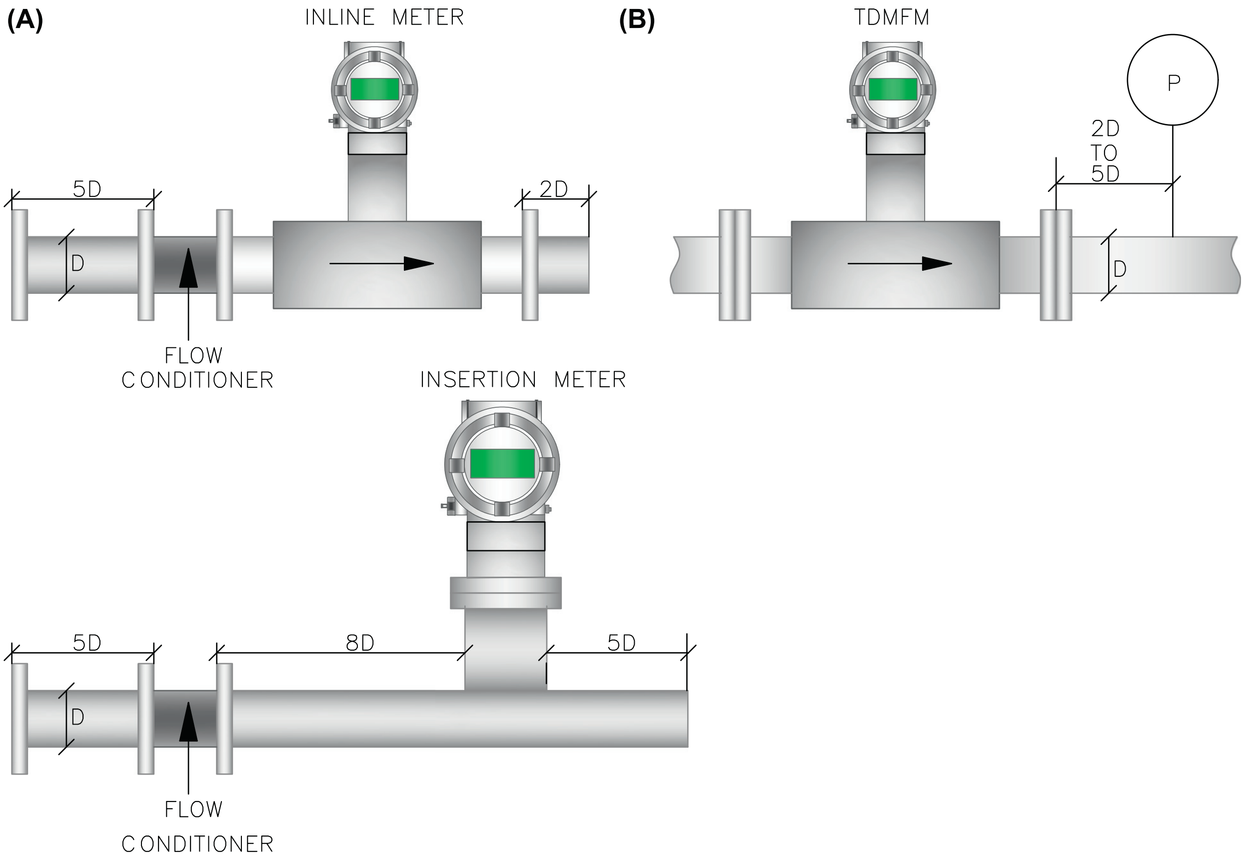

FIGURE VI/4.2.8-2 Flow conditioner and tapping point location. (A) Flow condition positions. (B) Tapping point at downstream.

TABLE VI/4.2.8-2 Straight Length Requirements for TDMFM (X Times Pipe OD "D")

Upstream	In-line TDMFM (XD)		Insertion TDMFM (XD)	
Obstruction Type	Upstream X	Downstream X	Upstream X	Downstream X
Reducer or expander	15(D)	2(D)	20(D)	5(D)
Single 90 degrees elbow/tee	15(D)	2(D)	20(D)	5(D)
Two elbow 90 degrees same plane	20(D)	2(D)	25(D)	5(D)
Two elbow 90 degrees different plane	35(D)	2(D)	40(D)	5(D)
Control valve/pressure regulator	50(D)	2(D)	50(D)	5(D)

ascertained it is necessary to follow the standard calibration procedure in situ or to remove the meter to the factory for calibration [16].

With our discussions on installation concluded here, we now take up the issue of calibration.

4.2.9 CALIBRATION OF FLOW METERS

It is standard practice to calibrate the meter with gas in the specified range of flow rate, with at least 10 different flow rates. Normally, gas calibrations are performed at standard conditions (STP) using "mercury ring" piston prover calibrators [1]. There are two kinds of calibration procedures: the closed loop calibration procedure and open loop method. For in-line meters both procedures are followed. For batch flow calibration only the open loop method is followed [16]. All such calibrations are NIST or other equivalent international traceable standards. The calibration data are kept in the instruments and certificates are issued. As it is based on the gas property, the convective heat transfer property of gas varies, so an instrument calibrated for air will not give the same accuracy for other gases. Each instrument is calibrated for a specified gas over the maximum flow rate specified. Recalibration of gas flow meters varies with application and normally lies within 6 months to 1 year.

With this the discussions on thermal dispersion type flow meter come to an end. In the following section general discussions on thermal flow meters shall be presented.

4.3.0 General Discussions on Thermal Mass Flow Meters

The majority of fluid flow meters are volumetric in nature. Since mass is an intrinsic property of material, measurement of mass flow meters, especially for fluids, have some additional advantages as requirements for compensations for density variations with changes in operating conditions are not called for. Coriolis flow meters find major applications in liquids, similarly, thermal flow meters find major application areas in gas. In this section short discussions will be presented on the special advantages of thermal mass flow over other technologies and area of applications. During the discussions both types will be covered. However, since immersible thermal or thermal dispersion types find more applications in industrial scenarios, the emphasis will be on these.

4.3.1 ADVANTAGES OF THERMAL MASS FLOW METERS

Their major advantage comes from the fact that they can measure the flow at low gas pressure,

where Coriolis meters cannot work. In this section the advantages of thermal mass flow meters will be concentrated on.

1. **Direct mass flow:** Based on heat transfer, thermal mass flow meters measure the fluid (gas) mass flow rate. Since heat transfer is caused by the molecular mass flow of the fluid it gives direct mass flow measurement without any need for correction for pressure and temperature (required to take care of change of density) hence there is no expense for additional equipment/devices.
2. **Operating condition fluctuations:** The measurement is suitable for applications where there are fluctuations in temperature and/or pressure.
3. **No moving part:** Thermal flow measurement systems do not have any moving parts and hence are less prone to maintenance making them less expensive in the long term.
4. **Performance:** Thermal mass flow meters provide good performance with good overall accuracy in the tune of 1% AR and good repeatability.
5. **Turndown ratio:** Thermal flow meters are not linear and need to be linearized at the transmitter. However, this is an advantage for measurement as it can provide high sensitivity at low flow and give a good turndown ratio. A turndown ratio of 100:1 is easily achievable and a turndown ratio of 150:1 is possible.
6. **Low-pressure measurement:** The thermal flow meter is capable of measuring mass flow at low fluid (gas) pressure where flow meters based on other technologies do not perform well.
7. **Low-flow sensitivity:** Thermal flow meters show very good sensitivity toward low flow. They can measure flow with fluid velocity as low as 0.05 m/s. For this reason it finds its applications in special measurement types such as in semiconductor areas, where thermal flow meters find extensive use.
8. **Special flow applications:** Thermal flow meters are well suited for flare gas/stack gas applications including emission-monitoring services.
9. **Low-pressure drop:** Industrial thermal mass flow meters have low-pressure drop, especially for insertion type.
10. **Insertion type:** Insertion type thermal mass flow meters can cater to flow in large-diameter pipes and can be fitted in circular pipes or rectangular ducts with minimum pressure loss. Hot tap design is possible, meaning no time loss for replacement of retractable probes.
11. **Easier installation and lower cost of installation:** Installation is easy and cheaper.

4.3.2 LIMITATIONS OF THERMAL MASS FLOW

There are a few limitations to the type of meter in question. These include the following:

Clean gas and nonabrasive fluid: The use of thermal flow metering is mainly restricted to clean and nonabrasive fluids. There are limited uses in dirty gas/liquid with the help of a filter trap, etc.

Accuracy: For measurement with precise accuracy these meters do not find applications as thermal mass flow meters offer medium accuracy.

Fluid: This is applicable to gas mainly and limited liquids. Steam, etc. cannot be measured.

Gas property: The thermal and other gas properties must be known for measurement to be completed. If calibration is done for some gas other than actual one and necessary conversion factor is not utilized, then there would be inaccuracy in measurement.

Initial cost: Initial cost is relatively higher than many other flow meters.

4.3.3 MAJOR APPLICATION AREAS

As mentioned earlier, thermal mass flow meters have limited applications in liquid flow measurement. Thermal mass flow meters are mainly used for gas flow measurement. The major applications areas for thermal mass flow meters include but are not limited to the following:

1. Compressed air distribution and balancing;
2. Measurement of natural gas consumption, e.g., burner gas flow;
3. Measurement of stack gas and flare gas;
4. Air separation system;
5. Digester gas, biogas, and aeration measurements in sewage treatment/wastewater plants;
6. Gas flow in chemical/process plants;
7. Measurement of toxic and corrosive gases and mixtures;
8. Gas flow mixing and blending;
9. Gas flow control in conjunction with electromagnetic valves;
10. Semiconductor industry;
11. Measurement of gas in carbonization in soft drink production and breweries;
12. Gas leakage detection system;
13. Gas recovery system;
14. Gas flow in chemical/process/pharmaceutical plants.

4.3.4 DIGITAL METER CONFIGURATION

This application often requires field adjustment of the meter, and is occasionally called field calibration. However, this is not always the correct. To perform a meter calibration, a test bench and set are needed. In reality what people want to do is to configure digital meters for a specific application. They often wish to change the line size, zero/span adjustments, installation factors, gas conversion factor, etc. All these fall under configuration, and a simple configurator can do this. This should not be confused with calibration.

With this the discussions on thermal flow meters and as such discussions on mass flow meters come to an end and we now explore and investigate how slurry flow can be measured and controlled in Chapter VII.

LIST OF ABBREVIATIONS

ABS Absolute
AC Alternating current
ADC Analog to digital converter
AR Actual reading (in connection with accuracy)
CMFM Coriolis mass flow meter
CMRR Common mode rejection ratio
CMV Common mode voltage
CPM Constant power mode
CS Carbon steel
CTM Constant temperature mode
DC Direct current
DP Differential pressure
DPT Differential pressure transmitter/transducer
DSP Digital signal processing
EMC Electromagnetic compatibility
EPDM Ethylene propylenediene monomer (rubber)
ETFE Ethylene tetrafluoroethylene (type of plastic)
FC Fail to close (for valve)
FO Fail to open (for valve)
FSD Full-scale division (in connection with accuracy)
FSK Frequency shift keying (digital communication)
FTR Flow turndown ratio
HFO Heavy fuel oil
HVAC Heating ventilation and air conditioning
IC Integrated chip/internal combustion (engine)
ID Internal diameter
I/O Input/output
LCD Liquid crystal display
LED Light-emitting diode
LFE Laminar flow element
LHS Left-hand side
LSHS Low sulfur heavy stock
LVDT Linear variable differential transformer
MTR Measurement turndown ratio
MUX Multiplexer
NB Nominal bore
OD Outer diameter
PD Positive displacement (meter)
PFA Perfluoroalkoxy alkanes
PRTD Platinum resistance temperature detector
PTFE Polytetrafluoroethylene
PVDF Polyvinylidene fluoride—plastic type
RF Raised face or radio frequency
RHS Right-hand side
RTD Resistance temperature detector
RTJ Ring tongue joint
SIL Safety integrity level
SS Stainless steel
STP Standard temperature and pressure (Fig. I/1.1.2-3)
T/C Thermocouple
TDMFM Thermal dispersion mass flow meter
TMFC Thermal mass flow controller
TMFM Thermal mass flow meter
US Ultrasonic/United States
VM Valve manifold
VTR Viscosity turndown ratio
WRT With respect to

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CHAPTER VII

COMPLEX AND SLURRY FLOW MEASUREMENT

Chapter Outline

1.0.0 INTRODUCTION TO RHEOLOGY AND RHEOLOGICAL PROPERTIES

Who does not like chocolate? I believe almost all people like to eat chocolate. There are various kinds of chocolate available in the market with different textures and qualities. Rheology is one of the main reasons for its different textures. From our day-to-day experience we know that dilute flour−water solutions are easy to flow but as more and more powder (flour) is added to make dough, it is not as easy to move. Mayonnaise and Indian yogurt ("doi" in Bengali) do not flow even under stress for a long time, but honey always flows. Similarly, if we look into the industrial scenario, one can observe that the flow and flowability of oil, cement slurry, water sand slurry, mining slurry, and slurry in a paper plant all have different flowability and flow characteristics. All such observations and problems are especially looked at in rheology, i.e., rheology can be seen as a division of engineering in which studies are carried out to see how the stress in a material or force applied to a material is related to deformation (change of shape) of the material and flowability. Here it is important to note that only basic ideas and working formula needed on rheology and fluid mechanics for *flow measurement and control* are covered, keeping in mind the objective of the book and the limits of the book volume. For more details on rheology and fluid mechanics standard books on the same may be consulted for further reading. The word rheology has its origin from Greek, where "rhe" means "flow." Therefore, *rheology is a branch of physics and engineering that deals with the*

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deformation and flow of matter, especially the non-Newtonian flow of liquids and the plastic flow of solids. Rheology also affects production processes greatly, especially where it is necessary to deal with slurry and non-Newtonian (refer to Subsection 1.1.2.5 of Chapter I) fluids. Rheology can affect processing, the texture of the final product, product pour, surface distortions, structure development, and strength, i.e., product quality.

Rheology can be conceived of as a systematic study to establish the relationship between the applied force or stress in a material and deformation (change of shape) of the material and flow characteristics. Although rheology is mainly applicable to liquid, it is also applicable to soft solids and even to solids in certain cases. This mainly applies to substances with a complex structure, such as mud, sludge, suspensions, polymers, etc. Thus, with the help of rheology it is possible to understand the kinds of flow and deformation effects exhibited by various slurry and other non-Newtonian fluids. With basic rheological knowledge it is possible to design and optimize the solution to problematic issues related to deformation and flow. The main *goal* of rheology is to establish the relationship between applied forces and geometrical deformations induced by these forces at any point in a fluid. The following are the major concerns and issues of rheology:

- The mathematical equations of such a relationship are referred to as the constitutive equations.
- Constitutive equations are used to solve problems related to continuum mechanics (defined in Fig. VII/1.0.0-1 may be refernced) of these materials.
- Constitutive equations are deployed to model the system as a part of continuum mechanics.

The majority of low-molecular-weight, organic and inorganic liquids, inorganic salts, molten metals and gases exhibit Newtonian flow characteristics, i.e., at constant temperature and pressure, in simple shear, the shear stress (σ) is proportional to the rate of shear ($\dot{\gamma}$) and the constant of proportionality is the familiar dynamic viscosity (η). These fluids are classically known as Newtonian fluids. On the other hand, many substances in industrial use such as foams, emulsions, dispersions and suspensions, slurries, polymeric melts, and solutions do not conform to the Newtonian law of linear relationship between shear stress (σ) and rate of shear ($\dot{\gamma}$). These fluids are variously known as non-Newtonian, nonlinear, complex, or rheological complex fluids.

First Formulated by French Mathematician and physicist Augaustin Louis Cauchy in the nineteenth century, Continuum mechanics is a branch of mechanics. Continuum mechanics is a combination of mathematics and physical laws to model large-scale behavior of matter subjected to mechanical loading. Fundamentally, it is a more generalized version of Newtonian mechanics or particle dynamics, having the same physical assumption; at the same time continuum mechanics adds further assumptions to describe the structure of matter. Although the fluids and solids exhibit different behaviors, both of them follow conservation of momentum and energy. Therefore, common governing laws for both fluids and solids are not something unexpected. Continuum mechanics brings a common framework based on fundamental laws of mechanics and thermodynamics. In spite of the fact that molecules are building blocks for both solids and fluids, the continuum mechanics framework is developed without considering the molecular nature of matter. Therefore, this unified framework also helps in the study of some complex materials, which exhibit both solid-and fluid-like behaviors, known as viscoelastic solids and viscoelastic fluids including non-Newtonian fluids.

FIGURE VII/1.0.0-1 Continuum mechanics.

The discussions so far have mainly been on the definitions of rheology and associated explanations. Now it is time to look into the issue in more detail.

1.0.1 FLUID CLASSIFICATION BY RHEOLOGY

1. **Stress strain and deformation of Newtonian fluids:** When external force is applied, before deformation occurs, there will some internal forces acting inside the body. Such internal forces give rise to stress, which is a measure of force per unit area (something similar to pressure). When stress happens in one direction it is shear stress. Strain is the deformation of internal molecules composing the body, i.e., relative displacement. In the case of solids the cohesive force is very strong, so when external force is applied there will be stress but the strain will be much less compared to fluids with a much lower cohesive force. From basic physics it is known that for ideally elastic bodies, there exists a linear relationship between force (stress) and relative deformation or strain. If F is the force applied on a body of length (L) perpendicular to area A then

$$\text{stress } \sigma = F/A \left(N/m^2\right) \text{ and strain } \varepsilon = \Delta L/L$$

By definition of Hook's law,

$$\text{Young's modulus E(in Pa)} = \frac{\sigma}{\varepsilon} = \frac{F \cdot L}{A \cdot \Delta L} \quad \text{(VII/1.0.1-1)}$$

So, what we see here is that when there is force applied on the elastic solid body there will be deformation. When the force is withdrawn the deformation will be reversed, unless it reaches the break point.

Now let us look at what happens to a liquid. On account of the lower cohesive force, liquid does not have proper shape. So, when force is applied to a Newtonian liquid it will start to flow. This is also a kind of deformation. This is called viscous deformation. Here the shear stress (σ) is proportional to the rate of discharge (D). In an electrical analogy: voltage (V) is proportional to current (I) and proportionality constant is resistance R, i.e., $V = IR$. Similarly, here the proportionality constant is viscosity (η).

$$\text{So, } \sigma = \eta D \text{ (or } \dot{\gamma}) \quad \text{(VII/1.0.1-2)}$$

here also, viscosity resists flow.

When the shear rate versus shear stress is plotted, a linear curve as shown in Fig. VII/1.0.1-1A will be available. The slope of the

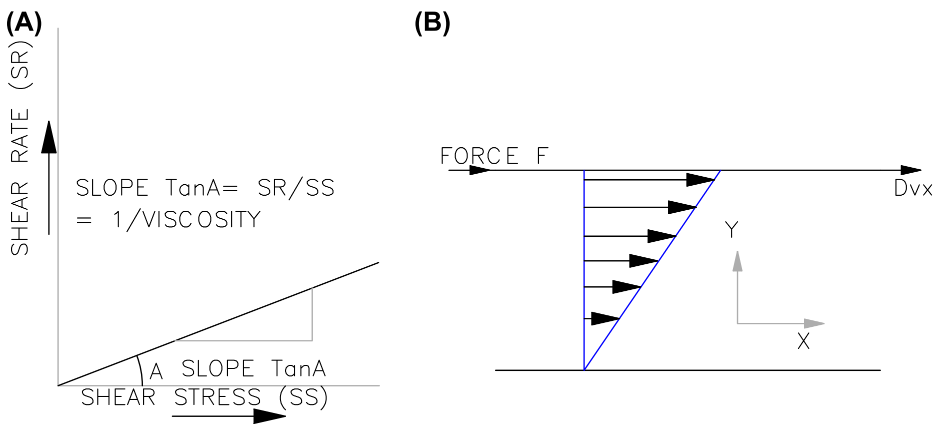


FIGURE VII/1.0.1-1 Newtonian fluid shear stress and flow. (A) Shear rate versus shear stress. (B) Shear flow (one direction).

curve will be 1/η as shown. From Chapter I it is clear that the flow could be laminar, transitional, or turbulent. In the case of laminar flow, as we have seen, fluid flows in layers parallel to the wall of the conduit with velocity zero at the wall to a maximum at the center in an increasing manner in the direction perpendicular to the wall. Therefore, shear strain perpendicular to the wall can be derived by $\gamma = \frac{dy}{dx}$ dimensionless quantity. How does this vary with time? With moving dx, by replacing dx by dx/dt, one obtains the velocity gradient, hence

$$\text{shear rate would be } D = \frac{dx}{dt} \Big/ dy = \frac{dv_x}{dy} \quad \text{(VII/1.0.1-3)}$$

Now, if we consider unidirectional flow then we get Fig. VII/1.0.1-1B. There is only one nonzero component of velocity, v_x, which is a function of y. Thus for yx shear in one direction we get,

$$\sigma_{yx} = \eta \cdot \dot{\gamma}_{yx} \quad \text{(VII/1.0.1-4)}$$

For the general case of three-dimensional flow there are six shearing and three normal components of the stress tensor (as $\sigma_{xx}, = \sigma_{yy}, = \sigma_{zz}, = 0$ as v varies in normal direction and $\sigma_{xy} = \sigma_{yx};\ \sigma_{yz} = \sigma_{zy};\ \sigma_{zx} = \sigma_{xz}$). Thus we find that in a generalized case for Newtonian flow, there will be a linear curve passing through zero with the gradient governed by scalar quantity viscosity.

2. **Stress strain and deformation of non-Newtonian fluid:** The two primary conditions for Newtonian fluids are:
   - Newtonian fluid are curve of $D(\dot{\gamma}) - \sigma$ is linear;
   - Curve of $D(\dot{\gamma}) - \sigma$ passes through origin.

   When either (or both) of the two above conditions are not satisfied by any fluid then the fluid is a non-Newtonian fluid, i.e., viscosity varies with the shear as $\eta = f(\sigma)$ or $\eta = f(D)$ and/or the curve does not pass through the origin. At this point the complexity starts, because there are several variations. Also, in certain cases the viscosity of some materials is not only a function of the flow conditions of geometry, shear rate, etc. These components also exhibit memory effect, i.e., history of the fluid element under consideration. Therefore, through rheology one may come to two broad divisions of non-Newtonian fluids. These divisions in reality are rather arbitrary without much scientific background [1]. These divisions are:
   - *Generalized Newtonian fluids (GNFs):* These are characterized by D at any point can be found from σ at that point (nonlinear relationship). Since its constitutive equation is basically derived from a generalized Newtonian equation, these are called generalized Newtonian fluids. Thus, these are purely viscous, inelastic, and time independent.
   - *Viscoelastic fluids (VEFs):* In these fluids both viscous fluid behavior as well as elastic solid-like behavior exist up to a certain shear stress. These are also time independent.
   - *Time-dependent fluid:* In this type of fluid there will be a nonlinear relationship between $D(\dot{\gamma})$ and σ and such a relationship shows further dependence on the duration of shearing and has a memory effect or kinematic history.

   In certain cases there could be a combination of more than one of the properties described above. Those fluids that exhibit a combination of properties from more than one of the above groups are described as complex fluids [2]. Some classify all other materials which have the ability to flow but do not follow a linear relation between deformation tensor and stress tensor as complex fluids [3].
3. **Complex fluid:** In our day-to-day life we come across a broad class of complex fluids such as yogurt, chocolate, cosmetics, colloidal suspensions, blood, and mucus. Complex fluid can be shear-thinning (Subsection 1.1.2.2)/shear-thickening (Subsection 1.1.2.3), or viscoelastic depending on the type and magnitude of the applied stress. Cornstarch suspensions,

for example, show shear-thickening and viscoelastic behavior. Macroscopically complex fluids are homogeneous but microscopically they have some disorder at the microscopic scale and possess a structure at an intermediate scale [4]. Complex fluids show many useful mechanical properties on account of their variety of structures. In colloidal crystals, for example, the intermediate scale is set by the size of the organized crystalline structure [4]. The flow behavior of a complex fluid is a function of the fluid microstructure. As stated at the initial stage of these discussions, the rheological properties of complex fluids are an important operating parameter for many industrial and manufacturing processes and often affect the texture and other qualities of the final product. Therefore, it is important to know and understand the physical and chemical forces which control the structural scale of complex fluids, so that they can be engineered to get materials with the unique desired mechanical properties. After shear stress exceeds the magnitude of yield stress (Subsection 1.0.2.3) drilling muds flow like a shear-thinning fluid. These flow properties allow the fluid to remove debris while cutting and drilling, yet keep the debris suspended during interruptions in drilling [4].

1.0.2 DISCUSSIONS ON FUNDAMENTAL TERMS IN RHEOLOGY

In this section a brief study will be outlined on the various forces, deformation, and classification of various matters in terms of elasticity. The discussion starts with various force types.

1. **Deformation force:** From the initial discussions it has been found that there has to be an applied force to cause fluid flow. These forces can be of different forms. In a conduit the applied force is due to the pressure difference across the ends of the conduit. This could be gravitational or natural. In a reactor it could be due to rotation of an impeller. Based on the effects these forces can be categorized as *compressive force*, *tensile force*, *shear force, bending moment*, or *torsion* force. Either way, when the force is applied, the matter resists deformation, so in order to establish flow it is necessary that this internal force or fluid friction is overcome. Deformation forces, often referred to as loading, can be changed to a force referred to as dynamic force, where the magnitude and/or direction is a function of time. Similarly, it could be static where there is no change in the magnitude or direction of the force. Since from the basic concept of viscosity it is clear that the force required is proportional to the area, it is more convenient to define the "stress" σ as the (force/unit area). Also, from the discussions in the above section it is clear that as the viscosity value increases there will be more stress necessary to cause deformation because of the higher internal friction.
2. **Deformation:** From the discussions in the previous section we can see that for a material which can flow, will have a deformation tensor due to the stress tensor to cause flow. Thus, whenever there is stress, there will be some deformation but that can happen only when the external force is larger than the internal force (in the form of resistance). At rest the shape and size of matter remain unchanged. When a material is at rest or equilibrium, i.e., it is not loaded, it maintains an interatom distance (in the order of 0.1 nm) so that the forces of repulsion between two adjacent atoms balance the forces of attraction. When the material is loaded, the atoms are forced out of their equilibrium positions so that they are either parted or brought together until the forces generated between them (attraction or repulsion), respectively, balance the external force. Therefore, deformation could be conceived as a change in the shape and size of a body due to applied external forces (loading), which is a combination of internal and external forces. There are

many kinds of deformation as per fluid mechanics; these include *translation, linear, rotation*, and *angular deformation.* However, fundamentally these deformations are of two kinds, namely, permanent deformation and temporary deformation. Permanent deformation causes flow, while temporary deformation gives the elastic property of the material.

- *Permanent deformation (flow):* Permanent deformation is irreversible. This means that the shape will never revert to its original state, once the force is removed. Thus the energy for deformation energy cannot be recovered and it will cause the flow of material. Therefore, flow is a permanent deformation.
- *Temporary deformation:* Temporary deformation is reversible, meaning that when the force acting upon the body ceases or is withdrawn, the shape reverts to its original state. This means that the energy for deformation energy can be recovered.

  From the above discussions it has been found that on account of deformation force there will be deformations in material body which can be temporary and permanent. In the case of temporary deformation the elastic property of the material is shown, while permanent deformation will cause flow which is resisted by the viscosity of the material. Therefore, there should be two kinds of material body. However, in reality there are various other kinds of materials where combinations of the above deformations are noted. We now explore these.

3. **Yield stress:** *What do you call hair gel or thick pastes or mayonnaise or Indian yogurt (doi in Bengali)?* Are these materials soft solids or fluids? Frankly speaking, they feel more like soft solids than fluids. If we keep a hair gel bottle open and leave it on its side it will take a long time to really flow. *Why?* This is because some force, hence stress, is required to initiate flow (yield) in fluid or semisolid products. As already stated, there are a number of rheological properties which play an important role in the known behavioral properties of a material as it starts flowing from a static stage to a dynamic condition (the reverse is also true). This force or stress required to initiate flow of fluid and semisolid products obviously plays a great role not only in flow but is also an important issue in handling the material for storage, transfer, packaging, and the end-use performance of those materials. The stress at which a flow is initiated is referred to as the *yield stress*. Yield stress is dependent on the internal structure of the material, which must be overcome to initiate flow. Similarly, to stop flow after stress is withdrawn requires rebuilding the previous structure. The destruction and rebuilding of a structure are kinetic processes with characteristic relaxation times [5].

   Fig. VII/1.0.2-1A is a curve for shear rate versus shear stress. It is noted from this figure that when shear stress is increased there is no change up to a certain level, then after that there will be a change in the shear rate, meaning there will be a start of flow. The yield stress is the applied stress that must be exceeded, in order to initiate fluid flow. Prior to yield stress there will be a change in the internal structure of the material. Yield stress is a significant factor for pumping, spreading, coating, etc. in many industrial processes [6]. When stress versus time is plotted one gets Fig. VII/1.0.2-1B. This shows that if one goes on increasing stress on the material with time then initially the stress increases up to a certain maximum point, then there will be permanent deformation, and the flow starts and the stress level tends to decrease. The highest level in the stress versus time curve is the yield stress. Similarly, when the shear stress versus stress rate is plotted one gets the curve shown in Fig. VII/1.0.2-1C. Normally it will never

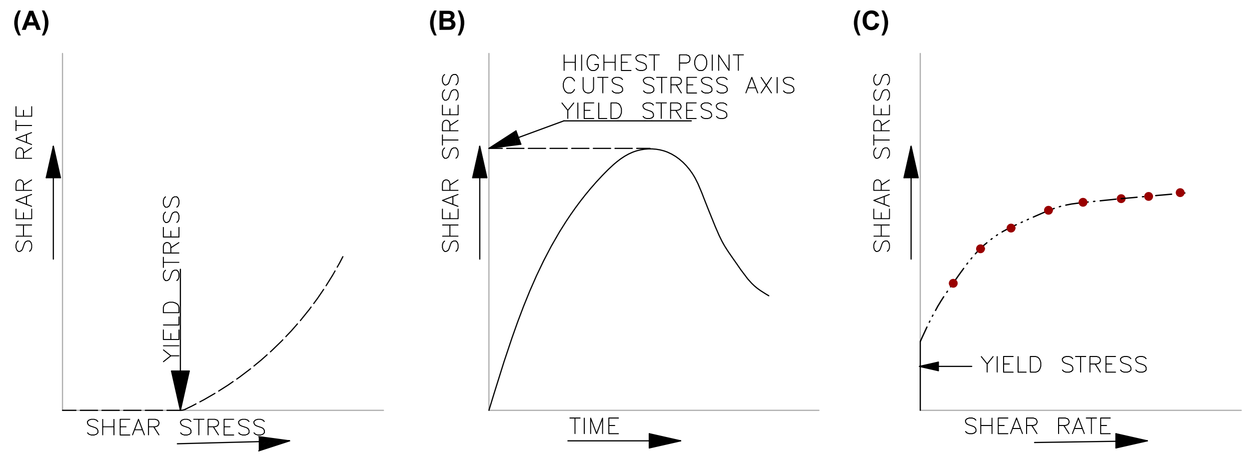


FIGURE VII/1.0.2-1 Yield stress (explained). (A) Shear rate versus stress. (B) Shear stress versus time. (C) Shear stress versus shear rate.

touch the stress axis, but if one extrapolates the same, the intersection point is referred to as the yield stress. Therefore, this discussion is concluded with the note that if the material sustains initial stress without flowing up to a certain level of stress, and starts flowing, on further increasing the stress then the limiting stress point is referred to as the *yield stress* and the fluid is called *yield-stress fluid*.

4. **Perfect elastic body:** From basic physics it is known that elasticity pertains to a rigid body. The elasticity property of a solid body gives it the tendency to return to its original shape after forces are applied on it. Thus, on removal of the external force a solid will return to its initial shape and size on account of its elastic property. Therefore, ideally an elastic/Hookean body will have only reversible deformation and in an ideal elastic body there will be a linear relation between stress and strain.
5. **Ideally viscous:** Newtonian fluids can be considered as an ideal viscous matter. As noted earlier, in a Newtonian fluid the shear rate is proportional to the shear stress passing through the origin. Newtonian viscosity is independent of strain or shear rate, meaning that when applied shear stress to a Newtonian fluid is doubled, the shear rate will also be doubled.
6. **Ideal plastic (Bingham plastic):** However, there are materials which do not follow exactly any of the above properties but follow a combination of both. There is no permanent deformation below the yield stress. When the applied stress is greater than the yield stress, the shear stress is directly proportional to the shear rate, i.e., it should follows Newton's law of viscosity above yield stress. Therefore, an ideal plastic can be represented by Eq. (VII/1.0.2-1).

$$\text{Stress } \sigma = \sigma_0 + \eta D \qquad \text{(VII/1.0.2-1)}$$

When Eq. (VII/1.0.2-1) is compared with Eq. (VII/1.0.1-2) one finds that it is the same as a Newtonian fluid, only it intercepts the shear−stress axis at any positive value as shown in Fig. VII/1.0.2-2. This positive intercept in the shear−stress axis represents the yield stress.

Such bodies are termed ideal **Bingham plastic**—named after the discoverer of a few paints in 1919 based on this type of property. Ideal Bingham plastic materials are rarely found in real-life materials. Fig. VII/1.0.2-2 has been presented to show various kinds of viscosity curves. In Fig. VII/1.0.2-2, a Newtonian curve is shown for comparison purposes only. As shown, except for Bingham plastic, all other curves are nonlinear in nature. Such nonlinear curves have been

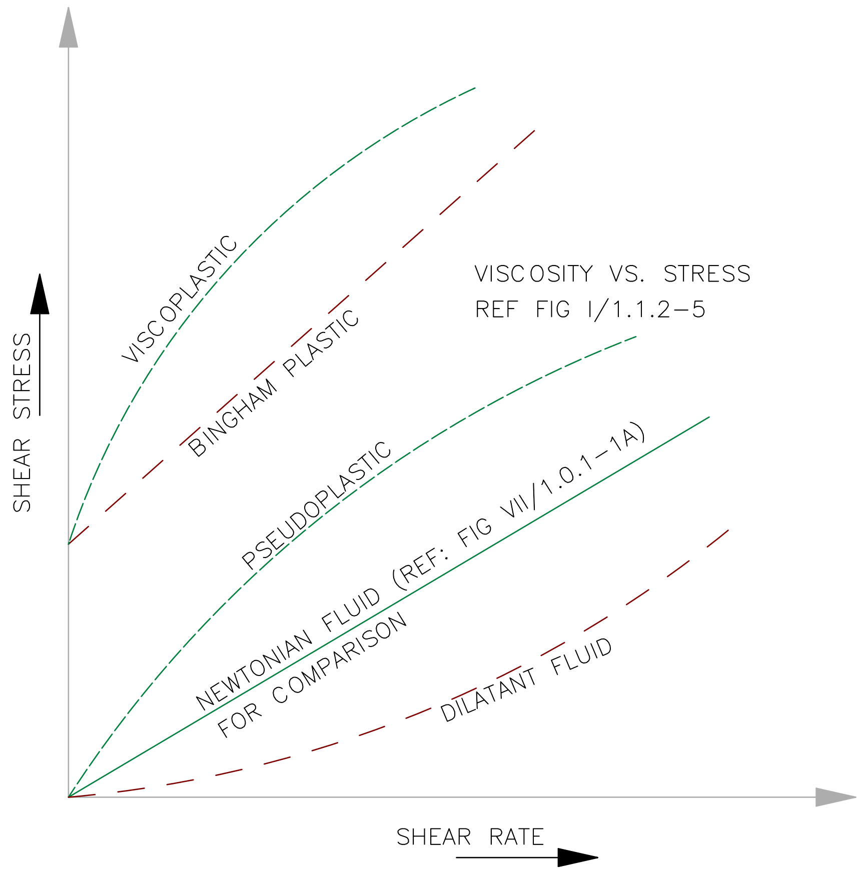


FIGURE VII/1.0.2-2 Nonlinear viscosity.

discussed in Section 1.2.0. Also note that real viscoplastic discussed in Subsection 1.0.2.7 is also not a linear curve for the stress versus strain rate.

7. **Viscoplastic material:** Even though the term "visco" is attached with this class of material, yet this may not be ideally linear but there are materials which are classified as viscoplastics which show a rate-dependent inelastic behavior of solids, i.e., above yield stress the shear rate varies with shear stress and may not be linear. Viscoplastic materials may or may not show shear-thinning behavior. In this connection it is necessary to understand plasticity. Plasticity is the ability of a body to change its shape and size permanently on application of an external force. When a force is applied in a plastic body, any two layers, of many layers, will slide from their crystal planes, to loosen their elastic limit, causing deformation in the body.
8. **Viscoelastic material:** As the name implies, viscoelastic materials exhibit both viscous fluid and elastic solid characteristics, i.e., these fluids show partial elastic recovery upon the removal of a deforming stress. Metals at high temperature, synthetic polymers, wood, and human tissue, fall under this category. Polymeric fluids often show strong viscoelastic effects which include shear-thinning, extension-thickening, normal stresses, and time-dependent rheology [2]. In viscoelastic materials, part of the deformation caused by shear stress is elastic, therefore it will return to zero when the force is removed. The remaining deformation will not return to zero when the force is removed. When the force is a constant force, the elastic displacement remains constant, whereas the

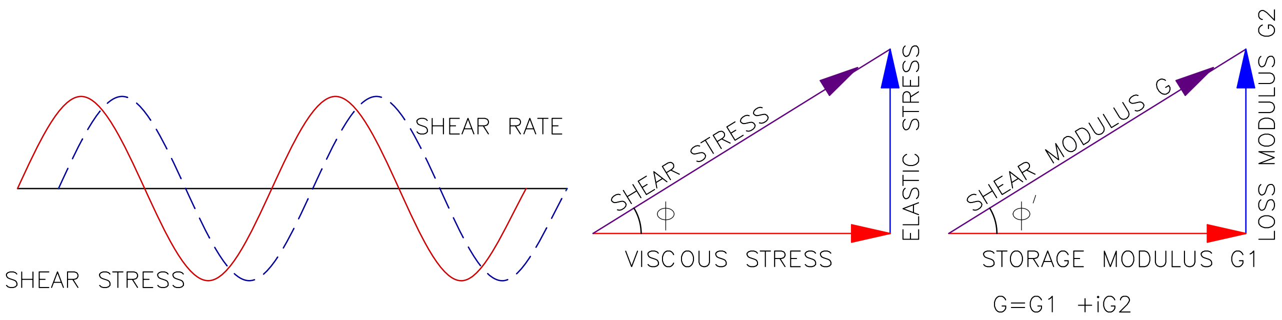


FIGURE VII/1.0.2-3 Viscoelastic characteristics.

sliding displacement continues to increase. When the force is periodic, e.g., sinusoidal, force will vary from positive to zero and then become negative, but viscosity is always positive, and hence may be lost as heat. Under such conditions the shear strain rate lags behind the force by a phase angle φ as shown in Fig. VII/1.0.2-3. Broadly speaking, viscoelastic materials can be linear or nonlinear. Linear is only possible where the strain is very small. The rheology of nonlinear viscoelasticity covers large deformation. Nonlinear viscoelastic constitutive equations are so complex that only a few problems can be solved analytically [2].

9. **Discussions on viscoelastic and viscoplastic materials:** Although many people confuse these, it is important to note that viscoelasticity and viscoplasticity are two different things, as is clear from plastic strain that occur when applies stress exceeds the yield stress. A viscoelastic material will return to its original shape (Kenvin model) on withdrawal of a deforming force (an elastic response) even though it will take time to do so (a viscous component). In contrast, a plastic material will not return to its original shape after the load is removed. A material can show a combination of elasticity and plasticity, in which case although it partly returns to its original shape on removal of the load, there will be some permanent deformation due to plastic deformation or molecular "slippage" of an irreversible nature. For a better understanding of this Fig. VII/1.0.2-3 has been presented. It is to be noted that these are schematic not to scale, nor are the origins of the curves shown. These are given here to show the nature of curves for different material behaviors only. In this connection Fig. VII/1.0.2-4 may be referenced.
10. **Memory effect/memory fluid:** Some materials, like paste (densely packed colloidal suspension) and egg white, may start to flow under the slightest stress, somewhat like a viscous fluid, yet they are not Newtonian fluids as these are well described by the memory fluid model. If the fluid is kept in a standstill condition for long time then only these fluids show isotropic stress (pressure), otherwise stress is nonlinear and a function of *deformation gradient history*. Therefore, these types of fluids are often called memory fluids. Naturally, in memory fluid the current value of stress cannot be determined by the current state of deformation, as it has memory of the deformation it had experienced previously. These fluids show elastic-like behavior, hence these are viscoelastic materials, e.g., clay. They conserve their shape over time periods of seconds or minutes and they can bounce or retract. Paste as discussed in Fig. VII/1.0.2-5 remembers the direction of external forces, such as vibration, flow, and magnetic field, and even after the external field is removed these can be seen as morphology of desiccation crack patterns. The exact reason for memory of flow is still under investigation. However, they behave like shear thinning when viscosity diminishes as shear is increased. Fluids like foams, micelles, slurries, pastes, gels, polymer solutions, etc. show a memory effect (Ref: Fig. VII/1.0.2-5).

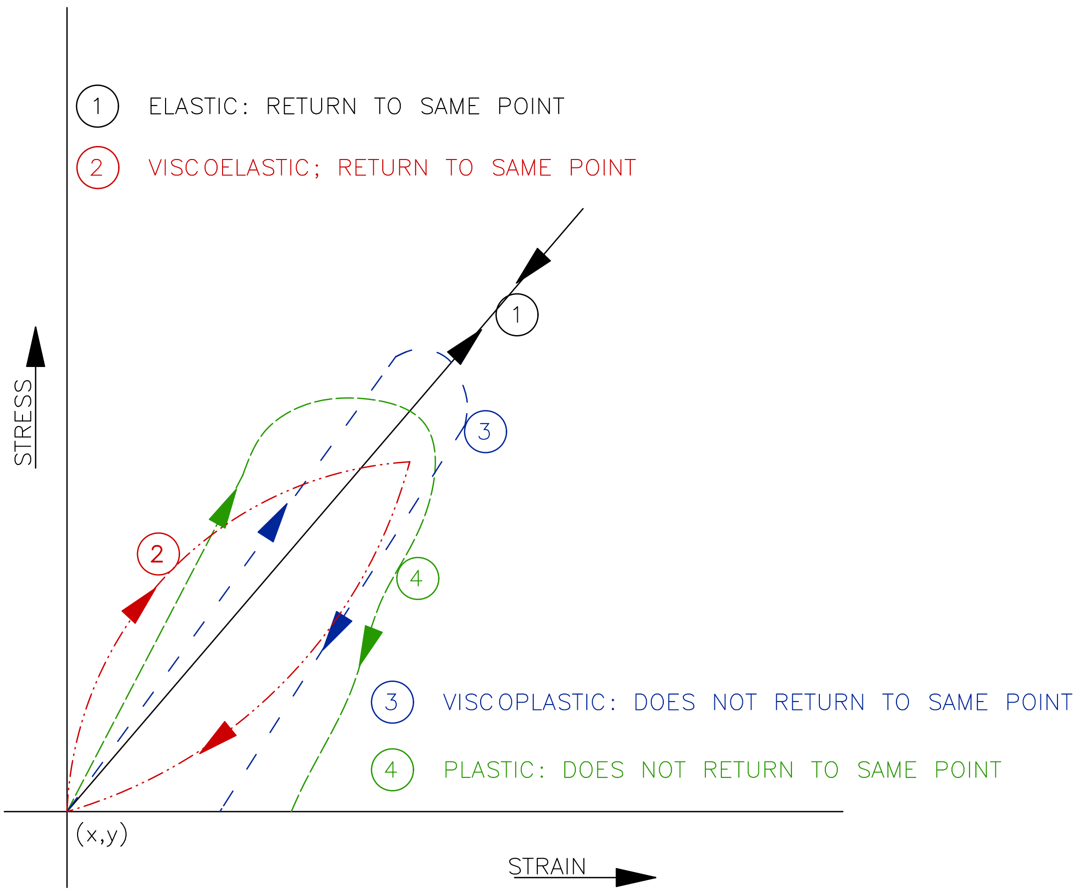


FIGURE VII/1.0.2-4 Stress–strain curves for different materials.

PASTE: *Densely packed Colloidal solution is referred to as Paste. Even after the removal of external fields paste can remember external forces such as Flow, Magnetic field, vibration, etc. These memories in the paste can be conceived as morphology of desiccation crack patterns. The Mechanism of memorizing flow is still not clear and is under investigation.*

FIGURE VII/1.0.2-5 Paste.

11. **Real materials:** In real life very few materials show the ideal characteristics discussed above, especially for materials with rheological properties. The majority of materials with rheological properties have a combination of the viscous, elastic, and plastic properties discussed above. Also these properties often change nonlinearly. Of these properties, viscosity has special significance for fluid flow, therefore this needs special discussion, as presented below. In Subsection 1.1.2.1 of Chapter I, some preliminary discussions on viscosity (mainly applicable for Newtonian fluids) have been presented; the discussion on viscosity presented here (mainly nonlinear viscosity for fluids under rheology) will supplement the said discussions in Chapter I.

1.1.0 Rheology and Viscosity

From the discussions above it is clear that viscosity is a measure of the fluid friction/resistance to flow. For any fluid flow, viscosity always plays a significant role. Naturally, detailed study on the

same is essential. In this section discussions on viscosity will be covered. In Chapter I a brief account on viscosity has been presented (in Sections 1.1.2 and 1.2.2). These were mainly pertinent to Newtonian fluids. Here also there will be some recaps of the same but the major emphasis here will be on the study of viscosity for nonlinear relations between shear stress and shear rate, i.e., non-Newtonian fluids and complex fluids in connection with rheology.

1.1.1 VISCOSITY CONCEPTUAL DETAILS AND INFLUENCING FACTORS

As indicated during the discussions in Chapter I, this is like the sliding of moving plates of area A relative to one another (two-plate model). If the gap between the plates, L, is filled with a fluid (liquid or gas), let one plate move with velocity v relative to the second stationary plate. At the initial instant, only the fluid very close to the moving plate will be in motion, while the rest of the fluid is at rest. The shear viscosity is measured at steady state, when the fluid velocity has become a linear function of the distance across the gap. The force required for the plate movement can be found from the following:

- The force required is proportional to the area of the plate A.
- The force is proportional to the velocity gradient (v/L).

As the force required is proportional to the area, it is more convenient to define the "stress" σ as the (force/unit area).

$$\text{So, stress } \sigma = \eta v/L = \eta \cdot \dot{\gamma} \quad \text{(VII/1.1.1-1)}$$

The coefficient of proportionality, η, is called the "shear viscosity" of the fluid. As seen from the above equation, when η is larger, the stress requirement for producing a given rate of deformation will be larger, and there is more internal friction in the fluid. Also, it can be seen from Eq. (VII/1.1.1-1) that viscosity has a strong dependence on shear rate $\left(\eta = \frac{\text{stress}}{\text{shear rate}}\right)$.

Viscosity depends on the microstructure, temperature, and range of the strain rate. Naturally, on account of the difference in microstructure, the viscosities of gas and liquid are different (ref: Section 1.1.2 of CHI). As the relationships of viscosity and temperature are different for gas and liquid based on their microstructure, these are given separately.

1. **Gas and temperature:** In gases, the molecular separation distance is larger compared to the molecular diameter and the interactions are primarily due to intermolecular collisions. If the velocity scale is small compared to the fluctuating velocity of the molecules, the viscosity of a gas is independent of the strain rate. However, it is strongly dependent on temperature (which can change the fluctuating velocity of the molecules). Viscosity of gases increases ***proportional to*** $\sqrt{T}$, where T is the absolute temperature in Kelvin.
2. **Liquids and temperature:** In contrast to gas, separation distance is comparable to the molecular diameter. Therefore, the viscosity has a strong dependence on the temperature and strain rate. Naturally, at higher temperatures, it is easier to slide one layer passed over the other; also, molecules will have a higher fluctuating velocity. This means the viscosity typically decreases with an increase in temperature. Here another factor is known as the "*hoping mechanism*" in liquids, for which the temperature—viscosity relationship is given by:

$$\eta = Ae^{-\left(\frac{B}{T}\right)} \quad \text{(VII/1.1.1-2)}$$

   here, T is temperature in Kelvin, and A and B are constants.
3. **Viscosity and pressure:** Viscosity generally increases exponentially with pressure as the internal gap decreases on account of compression and internal force increases. However, the influence on pressure on viscosity is small when compared with that of temperature, especially for a liquid which is incompressible. A pressure difference of 0.1—200 MPa can cause viscosity change in the tune of 3—5 times. However, in the case of fluids with high viscosity this is not the case and such increase may be more than discussed above. In most practical cases the influence of pressure is ignored.

4. **Solution concentration and viscosity:** Viscosity of solutions, e.g., polymer solutions, the relationship between viscosity with concentration is generally linear up to a certain viscosity values (of about *twice* that of water) [7]. The viscosity increases with concentrations up to a value where, due to stress, the elongated molecular volumes overlap. At higher concentrations (>critical concentration C) all the polymer molecules in the solution effectively overlap. The solution behavior becomes mainly elastic (from viscous) with the viscosity (η_0 at zero stress) being mainly governed by the mobility of the polymer molecules. Critical concentration is a function of shear rare.
5. **External force/stress:** Viscosity not only depends on shear strain but also on shear stress, i.e., external forces acting upon the material to make it to flow. Here both the intensity and the duration are important for non Newtonian fluids discussed below. However, Newtonian fluids are independent of this.
6. **Viscosity and shear rate:** From a rheological point of view the shear rate dependence of fluids and viscosity is an important consideration, because it makes the distinctions between Newtonian fluids, non-Newtonian fluids and complex fluids. In view of Eqs. (VII/1.1.1-1) and (VII/1.0.1-2) it is clear that Newtonian fluids are mainly characterized by:
   - the viscosity is independent of shear rate;
   - the viscosity is independent of time of shear at a constant shear rate;
   - the shear stress and strain curve is linear passing through the origin.

   Any liquid showing a deviation from this behavior is a non-Newtonian fluids, which is investigated in rheology. If from Eq. (VII/1.1.1-1) one plots viscosity as a function of shear rate one would get Fig. VII/1.1.1-1, where Newtonian fluid is constant at a value C (viscosity of the material) parallel to abscissa indication not changing with shear rate. Two other types are non-Newtonian fluid shear thinning and shear thickening as shown.

   We now look into details about nonlinear viscosity.

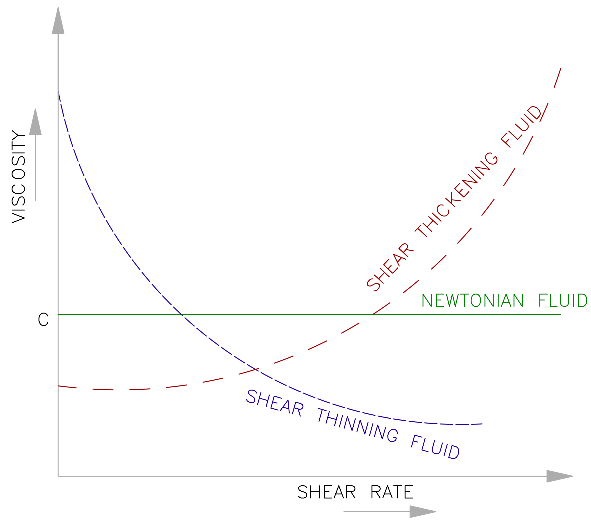


FIGURE VII/1.1.1-1 Viscosity function of shear rate.

1.1.2 NON-NEWTONIAN TIME-INDEPENDENT VISCOSITY

The discussions begin with reference to Fig. VII/1.0.2-2, where a curve for Newtonian fluid has been shown for comparison purposes only. All non-Newtonian materials have nonlinear characteristics for viscosity (exception Bingham plastic). Another interesting fact is that all non-Newtonian materials have high viscosity (but the reverse may not be true). In all these cases viscosity (η) is a function of shear stress (σ) or shear rate (D or $\dot{\gamma}$): $\eta = f(\sigma)$ or $\eta = f(D \text{ or } \dot{\gamma})$. From the discussions on viscosity, the dependence of viscosity on material microstructure has been noted. Therefore, based on the enlargement and breakdown of these material microstructures there are two clear divisions of nonlinear viscosity characteristics of materials. The main divisions are shear thinning or pseudoplastic and shear thickening or dilatant. We now investigate these types with some additional detail. However, two other terms that frequently arise when dealing with non-Newtonian flow are first defined.

1. **Important terms for viscosity:** The following terms are important for polymer solutions and other non-Newtonian flow characteristics.

- *Relative viscosity:* This is an important parameter for polymer solutions. Relative viscosity is calculated by dividing the solution viscosity (η_{ps}) with the viscosity of the pure solvent (η_s).

  Therefore, the relative viscosity for a polymer solution is given by:

$$\eta_r = \frac{\eta_{ps}}{\eta_s} \qquad \text{(VII/1.1.2-1)}$$

- *Apparent viscosity:* As long as the dynamic or shear viscosity η is independent of shear rate then it can be easily defined, however when the viscosity is influenced by the shear rate it is not easy to specify the viscosity. In such situations it is important to note that the values are different from the constant ones of an ideally viscous fluid. The values obtained are "apparent viscosity" values. They represent one point of the viscosity function only and the shear conditions need to be specified for apparent viscosity values. What is apparent viscosity? In line with International union of pure and applied chemistry (IUPAC) definition: the ratio of stress to rate of strain is calculated from measurements of forces and velocities as though the liquid were Newtonian.

$$\eta = \frac{(\sigma - \sigma_0)^n}{\dot{\gamma}} \qquad \text{(VII/1.1.2-2)}$$

  This is a general equation, where σ_0 represents yield stress; therefore Eq. VII/1.1.2-2 is also valid for other systems.

2. **Shear thinning materials:** This is probably the most widely used time-independent non-Newtonian fluid behavior normally encountered fluid in day-to-day use and in industrial plants. In fluids showing "shear thinning" or "pseudo plastic" characteristics, the viscosity decreases as the strain rate is increased. The general shape of the curve is as shown in Fig. VII/1.1.2-1, which is basically a combination of the two sets of curves shown in Figs. VII/1.0.2-2 and VII/1.1.1-1 in one place for convenience. Variations of viscosity with stress have been detailed in Fig. I/1.1.2-5 also. Another point to be noted here is that it does not show yield stress. Therefore, from all these curves it can be seen that at very low shear rates, the viscosity is nearly a constant. This constant value is termed the "lower Newtonian region" or "first Newtonian region." It is characterized by an apparent viscosity η is defined as $\sigma/(\dot{\gamma} \text{ or } D)$, which gradually decreases with increasing shear rate. At low shear rates, i.e., at "lower Newtonian region" the apparent viscosity is independent of shear rate (zero shear viscosity, η_0).

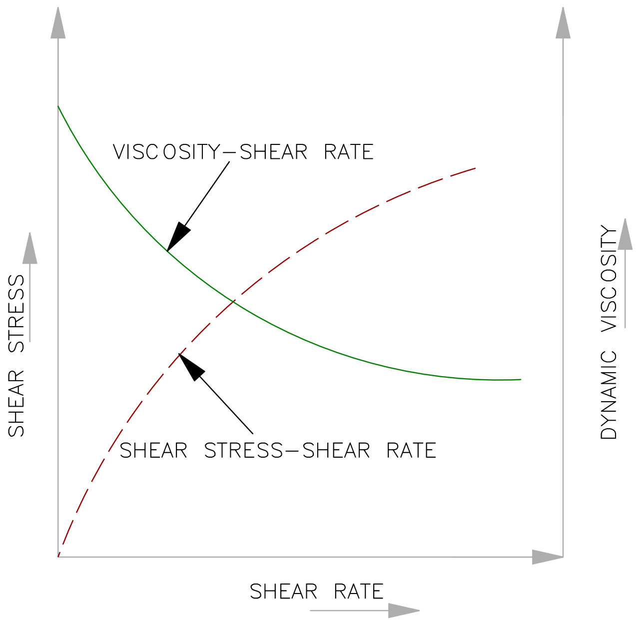


FIGURE VII/1.1.2-1 Shear thinning material.

$$\lim_{D \to 0} \frac{\sigma}{D} = \eta_0 \qquad \text{(VII/1.1.2-3)}$$

As the shear stress/shear rate is increased, there is a decrease in the viscosity, and the viscosity once again saturates to a constant value at higher shear rates, referred to as the "higher Newtonian region" [1]. Therefore, at very high shear rates (infinite shear viscosity, $\eta\infty$) they exhibit a similar situation, i.e.,

$$\lim_{D \to \infty} \frac{\sigma}{D} = \eta\infty \qquad \text{(VII/1.1.2-4)}$$

In most cases of polymer solution $\eta\infty$ is slightly higher than η_s (for solvent).

This type of fluid is represented well by a so-called "Ostwald de Weale" model or the power law model (model detailing is beyond

the scope of the book and a standard book on fluid mechanics for non-Newtonian fluid may be referenced), and is valid at intermediate values of strain rate, and n is the power law index.

As per "Ostwald de Weale" shear

$$\sigma = m \cdot (D)^n \qquad \text{(VII/1.1.2-5)}$$

and viscosity is given by

$$\eta = m \cdot (D)^{n-1} \qquad \text{(VII/1.1.2-6)}$$

here, n is the power law index and m is the consistency index. For $0 < n < 1$ will yield ($d\eta/dD < 0$), i.e., shear-thinning behavior fluids are characterized by a value of n smaller than unity. At this point Fig. I/1.1.2-7 may be referenced.

3. **Shear thickening materials:** Like shear thinning materials, shear thickening materials/fluids also show no yield stress, but their apparent viscosity increases with increasing shear rate. On account of this property this kind of fluid is named *shear-thickening*. In 1938, Freundlich et al. first observed shear thickening behavior in a concentrated solution.

Concentrated suspensions, for example, could show shear thickening behavior which could also result from flocculation of particles due to shear/the jamming of high aspect ratio particles due to rotation. This issue can also be explained easily. At rest there will be the least void space because the liquid can fill the void space. Also, at low shearing, i.e., at low flow, the liquid present can lubricate the motion of particles, so that friction between solid particles is avoided or reduced. However, when the flow is greater at higher shear the mixture dilates, and hence the available liquid becomes insufficient to fill the void space and prevent solid-to-solid contacts and friction. Thus there will be much larger shear stresses. This mechanism causes the apparent viscosity $\eta(=\sigma/\dot{\gamma})$ to rise rapidly with the increasing rate of shear [1]. After the observations of Hoffmann (1998), it is now generally accepted that an order–disorder transition is responsible for this rise in viscosity. His observation was that the flow instability caused the particles to break out of their ordered layers at some critical level of shear stress and jam into one another, thereby causing the rise in the viscosity. When compared with shear thinning material, shear thickening materials are usually represented by power law relations with an exponent n greater than 1, as will be clear from Fig. VII/1.1.2-2, which is basically a combination of the two sets of curves shown in Figs. VII/1.0.2-2 and VII/1.1.1-1 in one place for convenience. Variations of viscosity with stress have been detailed in Fig. I/1.1.2-5. Not much data about this are available as only a few materials of interest come under this category.

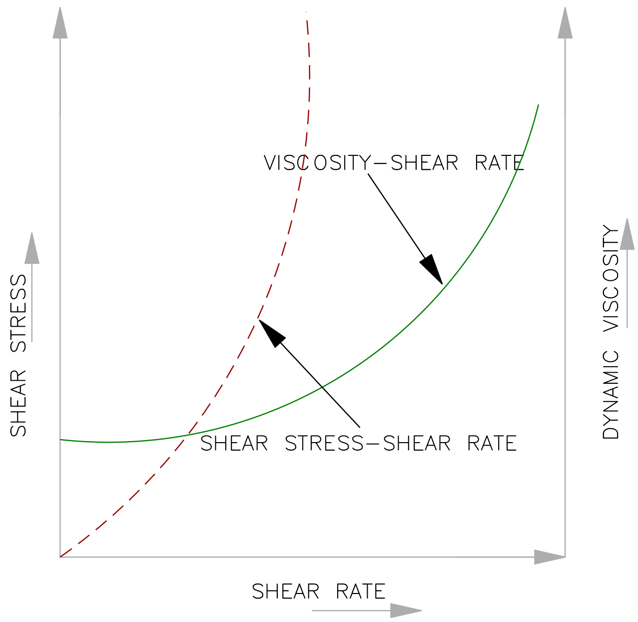


FIGURE VII/1.1.2-2 Shear thickening materials.

1.1.3 NON-NEWTONIAN TIME-DEPENDENT VISCOSITY

A change in fluid's viscosity over time indicates time-dependent behavior: a decrease being **thixotropic** and an increase being **rheopectic**. There are a number of materials, mostly in food, pharmaceutical and cosmetic products, and glue to name a few in this category that show flow characteristics which cannot be described by the

applied shear stress (σ) or the shear rate ($\dot{\gamma}$ or D) alone as these products also depend on the duration for which the fluid has been subjected to shearing as well as their previous kinematic history. From one's day-to-day experience with, e.g., body lotion, cream, or industrial products such as cement paste, coal water suspension, bentonite-in-water to name but a few, one can find that after a long time at rest (history) these products are subjected to shear (of constant value of D or $\dot{\gamma}$) it is observed that the viscosity of such kinds of product start decreasing. When the number of structural linkages starts breaking down, it reduces the viscosity changing rate with time and it approaches zero. At the same time as breakdown of the structural link, its rebuilding rate also increases. Therefore, a balance or equilibrium is reached finally. Similarly, a reverse phenomenon is also noticed in some materials, i.e., with shear rate. So as indicated above, based on the material behavior, there are two kinds of materials:

1. **Thixotropic:** these materials are characterized by the kind of materials which show a decrease in apparent viscosity against constant shear rate as discussed above.
2. **Rheopectic:** these materials are characterized by the kind of materials which show an increase in apparent viscosity against constant shear rate as discussed above.

The viscosity variations of both have been elaborated on in Fig. VII/1.1.3-1. Both materials exhibit a hysteresis curve as shown in Fig. VII/1.1.3-1. This signifies that when shear is increased from zero to a maximum value it will follow one path. After reaching the maximum, if the shear is withdrawn at the same rate then it will not follow the same path, instead there will be a hysteresis loop as shown in Fig. VII/1.1.3-1. This means that on withdrawal of shear some recovery is possible. The height, shape, and area enclosed by the loop depend on the rate of increase/decrease of the shear rate, the maximum value of the shear rate, and the past kinematic history of the sample, and it is not uncommon for the same fluid to display both thixotropy as well as rheopexy under appropriate concentration and shear rate combinations [1].

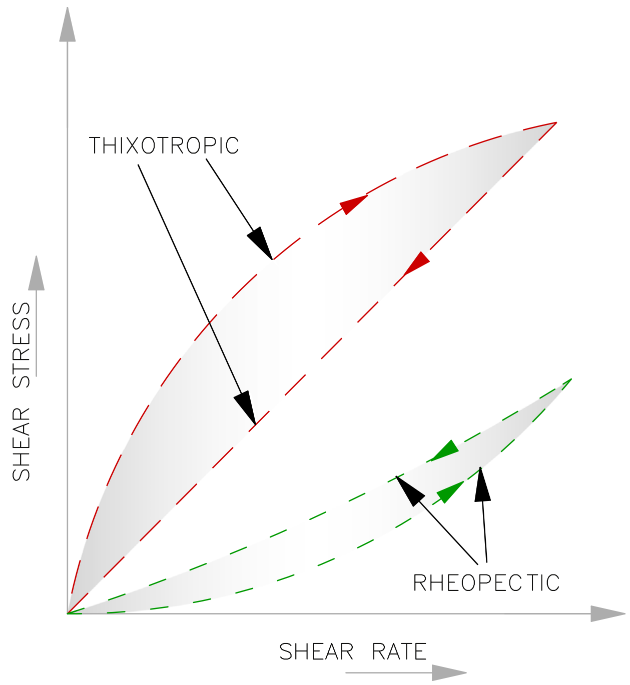


FIGURE VII/1.1.3-1 Time-dependent viscosity behavior.

With this, the discussions on viscosity come to an end and we now discuss viscoelasticity.

1.2.0 Viscoelasticity and Special Flow Styles

In this section short discussions will be presented on viscoelasticity, which is of special significance in rheology. Special flow types have also been included.

1.2.1 VISCOELASTICITY

Viscoelastic materials have been discussed in brief in Subsection 1.0.2.8, where it has been found that viscoelastic materials exhibit both viscous fluids and elastic solids. For this reason these materials are often referred to as soft solid materials. *Elastic behavior*: In an deal elastic solid, shear stress is directly proportional to strain; hence we get Eq. (VII/1.2.0-1).

For Young's modulus G;

$$\sigma_{xy} = G\cdot\frac{dx}{dy} = G\cdot\dot{\gamma}_{xy} \qquad \text{(VII/1.2.0-1)}$$

In the case of an ideal elastic solid, it regains its original form on removal of the stress. However, if the applied stress exceeds the characteristic yield stress of the material, complete recovery will not occur and **creep** will take place, i.e., the solid will have flowed [1]! Depending on the value of G, some of the substances are referred to as *soft solids*.

Viscosity behavior: we now look for viscosity in a Newtonian fluid where the shear stress is proportional to the shear rate, i.e.,

$$\sigma_{xy} = \eta\cdot\dot{\gamma}_{xy} \qquad \text{(VII/1.2.0-2)}$$

We have come across both these equations previously. Thus, perfectly viscous flow and perfectly elastic deformation are two limits for cases of viscoelastic behavior. Many materials show both elastic and viscous effects under appropriate circumstances. In the absence of thixotropy and rheopexy effects, the material is said to be viscoelastic [1]. In its simplest form, viscoelasticity can be modeled by combining Newton's law of viscosity for fluids, and Hook's law for elastic solids. However, the behavior of viscoelastic fluids is drastically different from that of Newtonian and inelastic non-Newtonian fluids. An ideal viscoelastic fluid should have rapid deformations as elastic solid and slow deformations as a Newtonian liquid. The ratio between the material time scale and the time scale of the flow is indicated by a nondimensional number: the Deborah or Weissenberg number. Therefore, based on the time scale of the flow, viscoelastic materials show mainly viscous or elastic behavior. Viscoelasticity includes normal stresses in shear flows, sensitivity to deformation type, and memory effects. These features underlie the observed peculiar viscoelastic phenomena, such as rod-climbing (Weissenberg effect), die swell, and open-channel siphon [2]. The majority of viscoelastic fluids show strain and extensional strain rate dependence. Viscoelastic materials at any instant depend on the recent history, i.e., they memorize the recent past. This is necessary for elastic materials because they have to remember their original shape so that on withdrawal of force they can return to their original shape. One feature of viscoelastic fluids worth noting is stress relaxation after a sudden shearing displacement where stress overshoots the maximum, then decays exponentially to a steady-state value. This phenomenon also takes place on cessation of steady shear flow, where stress decays over a finite measurable length of time. This reveals that viscoelastic fluids are able to store and release energy in contrast to inelastic fluids which react instantaneously to the imposed deformation [2]. Therefore, it is noted that viscoelastic material has a definite relaxation time lying between zero relaxation time for Newtonian fluids and infinite relaxation time for ideal elastic solids. The response of a material is governed by its structure and the kinematic conditions it is subjected to. Therefore, the distinction between an *elastic* and a *viscous* response is to some extent arbitrary and subjective [1]. It is also possible that the same material can exhibit both fluid-like and solid-like behavior in two different situations and conditions. Also, some materials, like polymeric melts and solutions, soap solutions, gels, synovial fluid, emulsions, foams, etc.) exhibit viscoelastic behavior.

1.2.2 SPECIAL FLOW STYLES

In this section special flow styles are considered. The discussions start with oscillatory motion associated with viscoelastic fluid.

1. **Oscillatory motion:** This is a characteristic feature of viscoelastic fluid. Brief details have been presented in Subsection 1.0.2.8 and Fig. VII/1.0.2-3. *The approach is very similar to that applied for* Resistanc (R), Inductor (L) and Capacitor (C) circuit commonly known as RLC *circuit with AC supply to find a final equation with phase change as the case may be.* In this case the approach will be to consider separately the elastic issue, i.e., Hookean equation and Newtonian fluid viscosity equation to finally arrive at viscoelastic flow.

Let the shear strain be sinusoidal for oscillatory motion then when γ_m is the amplitude and ω is the angle for frequency (f) (i.e., $\omega = 2\pi f$) of applied strain

$$\gamma = \gamma_m \sin \omega t \qquad \text{(VII/1.2.0-3)}$$

then utilizing Eq. (VII/1.2.0-1), one gets

$$\sigma = G\gamma_m \sin \omega t \qquad \text{(VII/1.2.0-4)}$$

Similarly, utilizing Eq. (VII/1.2.0-2) one gets $\sigma = \eta \cdot \dot{\gamma}$

$$\text{Now } \dot{\gamma} = \frac{d\gamma_m \sin \omega t}{dt} = \gamma_m \omega \sin(\pi/2 + \omega t)$$
$$= \sigma_m \sin(\pi/2 + \omega t) \qquad \text{(VII/1.2.0-5)}$$

There are two take away from here:

In the case of elastic shear it is in phase with shear rate and for viscosity shear stress is out of phase by $\pi/2$ with shear rate. The final vector is achieved by vectorial addition. Thus, the measurement of the phase angle $Ø'$ can vary from 0 (pure elastic) to $\pi/2$ (pure viscous). These have been elaborated on in Fig. VII/1.0.2-3.

2. **Elongation flow:** Another kind of flow is as extensional or stretching flow. In this type of flow, a fluid element is stretched in one or more directions. This type of flow occurs in coalescence of bubbles, enhanced oil recovery using polymer flooding. There are three types of elongational flow: uniaxial, biaxial, and planar.

   With these, discussions on rheology have now come to an end. With these ideas on rheology in mind let us now study slurry and special fluid flows.

2.0.0 DISCUSSION ON SLURRY FLOW

Prior to moving on to slurry flow measurement it is essential to know why slurry flow is necessary and what the types of slurry flow normally encountered in plant flow measurement are. Therefore, it is necessary to address the basics of slurry flow measurement. The discussions start with the basics of slurry flow.

2.1.0 Basics of Slurry Flow

In this section basic slurry flow measurements and their importance and variations are discussed. Prior to starting these discussions we familiarize the reader with a few terms normally encountered in slurry flow measurement and controls.

2.1.1 TERMS FREQUENTLY USED FOR SLURRY FLOW MEASUREMENT

The following are a few common terms encountered in slurry flow measurements:

1. **Critical carrying velocity:** This represents the mean velocity of the specific slurry in conduit, below which there will be separation and solid liquid. Above the critical carrying velocity the solids phase remains in suspension.
2. **Effective particle diameter:** This represents the average particle size used to describe the behavior of a mixture containing various sizes of particles in a slurry.
3. **Friction characteristics:** As the name implies this is the resistance to flow, exhibited by the mixture at various flows.
4. **Heterogeneous and homogeneous mixture:** In a mixture when solids and liquids are not uniformly distributed this is a *heterogeneous mixture*, in contrast, when solids and liquids are uniformly distributed it is a *homogeneous mixture.*
5. **Homogeneous and nonhomogeneous flow (fully suspended):** Slurry flow in which the solids are thoroughly mixed with the flowing stream and a negligible amount of the solids are sliding along the conduit wall is *homogeneous* flow. In contrast, in slurry flow in which the solids are stratified, with a portion of the solids sliding along the conduit wall, this is referred to as *nonhomogeneous flow* or *flow with partially suspended solids.*
6. **Percent solid by volume:** This is the ratio of the actual volume of the solid material and volume of slurry, multiplied by 100.
7. **Percent solid by weight:** This is the ratio of actual weight of the solid material and weight of slurry, multiplied by 100.

8. **Saltation:** This is a condition which exists in a moving stream of slurry when solids settle in the bottom of the stream in random agglomerations which build up and wash away with irregular frequency. In this connection Fig. VII/2.2.0-2 may be referenced.
9. **Settling velocity:** As the name implies, this refers to the velocity at which the solids in slurry move to the bottom of a container of liquid in rest (not in motion). This is less than the critical carrying velocity defined in Subsection 2.1.1.1 above.

2.1.2 OBJECTIVE AND CLASSIFICATION OF SLURRY FLOW

According to Webster, a watery mixture of insoluble matter (such as mud, lime, or plaster of Paris) is referred to as slurry. However, it is not necessary for it to be watery, only that it is with another substance also, e.g., offshore mud with an oil base and another chemical base such as a synthetic base. So, for simplicity, the flow of solid particles held in suspension in the carrier liquid is usually conceived of as *slurry flow*. Thus, by definition basically slurry flow involves the flow of a variety of liquids carrying dispersed suspended solid particles. Such transportation takes place on account of the drag and pressure forces of the liquid acting on the particles. The *objective* of these slurry flows could be transportation of bulk-solids and/or physical or chemical processes between carrier liquid and solids. As this is not pure liquid flow and two superimposed phases influence one another, the complete range of velocity is not possible. Therefore it is necessary to ensure the two phases are harmonized to avoid any blockage and that flow is continued. Two important parameters for slurry flow are:

- **Pipe Reynolds number:** This represents the total mixture flow, and hence Reynolds number; and
- **Particle Reynolds number:** This represents the relative Reynolds number of the solid particles and the liquid.

Also, there are a number of characteristics of the slurry and of the system that must be known for slurry flow measurement. Some of these important parameters are as follows:

- **Particle size and distribution:** It is necessary to know the particle size (diameter) and distribution is a measure of the percentage of particles in the slurry with a certain size or smaller.
- **Mass fraction of small particles:** It is important to note the fraction of particles smaller than 75 μm in slurry. Particles smaller than 75 μm somewhat facilitate the transport of larger particles. However, when the percentage of particles smaller than 75 μm exceeds 50%, the character of the slurry changes (towards nonsettling).
- **Concentration of solid:** This can be measured in terms of volume or by weight (Subsections 2.1.1.6 and 2.1.1.7).
- **Specific gravity:** Specific gravity of slurry, and that of solids and carrier liquid.
- **Particle shape:** The shape of the particles is also very significant for the behavior of the slurry.

Based on the various parameter discussed and characteristics of slurry flow, slurry can broadly be divided into two categories: nonsettling slurries and settling slurries. Within nonsettling slurries there is a division into slow-settling slurry and nonsettling slurry. In the case of slow-settling slurry where there is partial stratification, calculations need to be carried out in a special way. Two major parameters which actually create such division are: slurry *particle settling velocity* and s*olids concentration*.

1. **Settling slurry:** In settling slurry the solids will move to the bottom of the conduit at a discernible rate (but fast enough in time relevant to the process). However, it will remain in suspension by turbulence or when the slurry is agitated constantly. Usually particle size is greater than 100 μm and these are normally pseudo-homogeneous (mixture with solid particle in suspension with more concentration

towards bottom of the pipe) or heterogeneous (mixture in which the solids are not uniformly distributed and tend to be more concentrated in the bottom of the pipe) mixtures. Settling slurries show somewhat two-phase behavior. There are a number of factors listed below that affect the settling of solids:

- Solid concentration;
- Nature of carrying fluid;
- Particle−particle interaction;
- Particle−liquid interaction;
- Solid properties, e.g., particle shape and size;
- Particle density, size distribution.

The flow pattern of settling slurries is quite complex in nature. For settling slurries route selection of piping is important and the slope is restricted to between 10% and 16%. The following factors are important for determining the flow pattern in slurry flow:

- Properties of carrier fluid;
- Properties solid in the mixture;
- Superficial velocity;
- Slurry solid concentration.

At one extreme, the solids are present as a gravity bed. Such a flow regime is referred to as fully segregated or two-layered (sliding bed/stationary bed). At the other extreme,

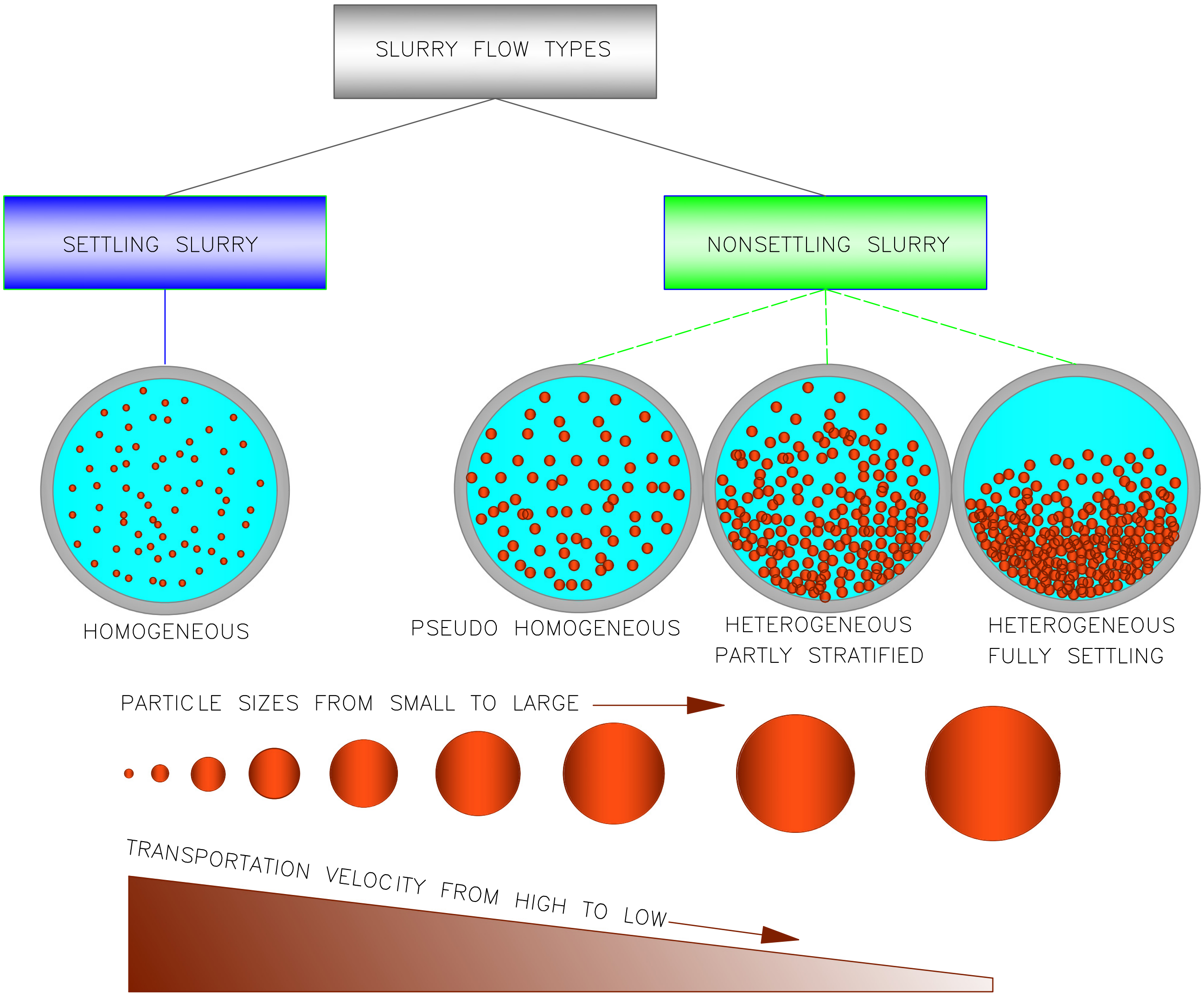


FIGURE VII/2.1.2-1 Settling and nonsettling slurry.

very high velocities with favorable solid and liquid properties, the solids may approach a *pseudo-homogeneous flow* [8]. When the superficial velocity of settling slurry is reduced, with a minimum in the hydraulic gradient, the bed formation of solids occurs in the pipe.

2. **Nonsettling slurry:** Alumina red mud, phosphate clay, tar sand, tar sand manure, etc. are examples of various nonsettling slurries normally encountered in industries and process plants. These are slurries in which the solids will not settle to the bottom of the conduit, but will remain in suspension, without agitation, for long periods of time. It is normally a homogeneous (a mixture in which solids are uniformly distributed), viscous fluid mixture, i.e., near uniform distribution of particles. It also shows axis-symmetric velocity distribution distributions in pipelines. Nonsettling slurries may behave like Newtonian or special non-Newtonian fluids [9] and are often treated as pseudo-fluid. However, nonsettling slurries are characterized mainly by non-Newtonian fluid. Based on rheological properties, nonsettling slurry flows can be laminar or turbulent, but the mixture will not segregate under any circumstances and velocity is selected mainly based on cost [9]. It is of utmost importance to decide if the flow is in the transition stage because at this point the flow equation will change. Unlike settling slurries, for nonsettling slurries there is no slope restriction for an inclined pipe.

Typical slurry flow classification and transportation velocity variations normally encountered in slurry flow are depicted in Fig. VII/2.1.2-1.

It is now time to look into the details of slurry flow, so we concentrate on solid liquid flow and flow regime in the subsequent section.

2.2.0 Solid–Liquid Flow Regime

Slurry flow is basically a two-phase flow of liquid and solids. Such types of flow are frequently encountered in many industries such as thermal and nuclear power plants, mining, offshore drilling, petroleum, and chemical industries, to name but a few. In industry, higher velocities are usually associated when transporting slurries, otherwise the solid particles may come out of suspension to cause pipe blockages. The complexities of slurry flows arise from various issues including the following:

1. The interactions between the phases;
2. The interactions of the phases with pipe walls;
3. Concentration of solids;
4. Pipe orientations;
5. Uncertainty of results from various models.

There are a number of flow regimes applicable for slurry flow. The slurry flow regime is a function of the properties of solids relative to the carrier fluid. The flow regime affects the pressure drop due to flow rate so while using a differential pressure (DP) transmitter this should be borne in mind. The flow regime also affects the line pressure drop, pipe erosion, etc. Frankly speaking, because of the complex nature of slurry flow and the transition of flow regimes it is not possible to get a distinct flow regime classification in slurry flow. However, there is a common way of classifying them into various flow regimes as listed below.

2.2.1 HOMOGENEOUS FLOW

As the name implies, in homogeneous flow fine solid particles are distributed uniformly in the carrier liquid and show uniform distribution across the pipeline about the pipe axis. The major characteristics noted in homogeneous flow include the following:

1. Solids are fine particles of size generally <40 to 60 μm;
2. Solids are low-density solids;
3. High solid concentration in the slurry;
4. Normally show viscous behavior;
5. Low settling velocity ($<$turbulent mixture velocity).

As stated above, for persistence of homogeneous flow the mean velocity of the flow should be much higher than the settling velocity of fine

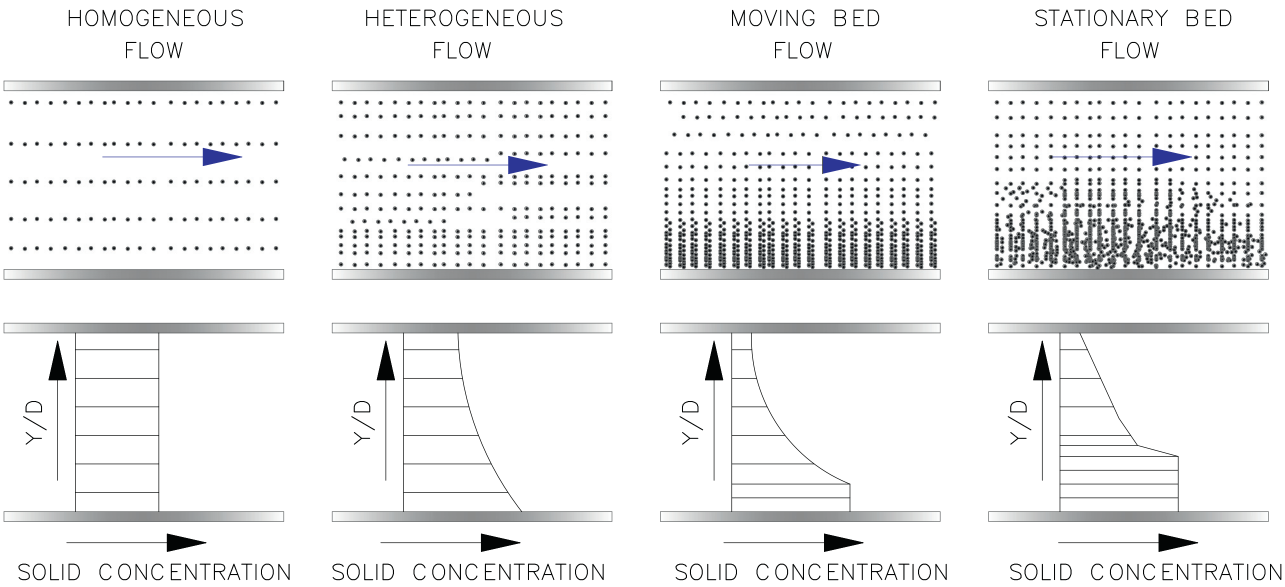


FIGURE VII/2.2.0-1 Classification of flow regime.

and light (low-density) solid particles. Particle concentration is high—around 60 wt% has been found [10]. Here concentration by weight is important. At higher concentration the mixture behaves like a viscous mixture. Even true homogeneous flow is not possible, yet this flow regime is treated as a single-phase flow. Rheological properties show non-Newtonian flow. A homogeneous flow regime has been depicted in Fig. VII/2.2.0-1. Here there is a uniform gradient for solid particle concentration.

2.2.2 HETEROGENEOUS FLOW

As heterogeneous is opposite to homogeneous, naturally the characteristics show opposite behaviors, as listed below:

- Solids are fine particles of size generally >40 to 60 μm;
- Sufficiently dense solid particles;
- Low solid concentration in the slurry.

On account of the above properties the distribution of solid particles is never uniform. Also, in a heterogeneous flow regime different phases retain their properties so as to be treated separately for analysis. In a heterogeneous flow regime the concentration of solid particles is normally less than 35% by wt. Such kinds of slurries are common amongst mining slurries [9]. As both phases retain their property, so when the mixture velocity decreases–due to lower flow coarser, denser solid particles tend to separate from the liquid, forming a concentration gradient in the vertical plane as depicted in Fig. VII/2.2.0-1. Denser particles settle at the bottom, while fine particles are in suspension, meaning that even though some deposit at the bottom, the majority of them will be in suspension. Naturally in this flow there will be a tendency for faster sedimentation. The concentration gradient will give rise to higher frictional loss. Heterogeneous flow is very complex characteristic flow. This may give rise to saltation, which is explained in Fig. VII/2.2.0-2.

In a heterogeneous flow regime there will be two distinct types of flow:

1. Heterogeneous mixture with saltation and rolling;
2. Heterogeneous mixture with all solids in suspension.

The Latin word ***Saltation*** in geology represents a specific type of particle transportation by fluid. It occurs when loose material is removed from a bed and carried by fluid, before being transported back to the surface. Hence this is possible for loose particles in fluid.

Creep: At low velocity of the fluid the energy is insufficient and the loose particles can only roll downstream, staying in contact with the surface. This is called Creep.

Saltation: However, when fluid velocity attends a critical value, when it can impart higher energy so that the drag and lifting force exerted by the fluid are sufficient to lift some particles from the surface, so that particles are accelerated by the fluid energy and are also pulled down by the gravity, sending the particle in to *a trajectory*. Such a method of Transportation of particles is referred to as ***Saltation***. Pebble transportation by river or sand drift in desert are natural examples. This can happen in slurry flow also.

FIGURE VII/2.2.0-2 Creep and saltation phenomenon.

2.2.3 INTERMEDIATE FLOW REGIME

There is no specific defined flow regime called an intermediate flow regime. The term settling and nonsetting slurries are often synonymously used as homogeneous and heterogeneous slurries [9]. However, in slurries if there is a large fraction of fine particles along with good quantities of coarse particles, then such an intermediate flow regime may occur. In such cases fine particles may be uniformly mixed in the slurry, whereas coarse particles may be in a heterogeneous mix. Also, if the flow velocity is insufficient then fine particles may deposit in the bed. Many mining slurries of this kind may be found.

2.2.4 FLOW WITH MOVING BED

A moving bed is observed in heterogeneous flow regime, when the flow velocity of the heterogeneous mixture is reduced below the deposition velocity, larger and denser solid particles will start depositing at the bottom of the conduit forming a bed. The denser, coarser particles deposit on the lower side of the pipe. The bed as a whole will move or slide at the bottom of the conduit on account of the shear force of the moving bed which is quite large. The lower part of the bed has the maximum packing bed and the upper part has a heterogeneous mixture. Therefore, the concentration gradient as shown in Fig. VII/2.2.0-1 exists due to the denser particles.

2.2.5 FLOW WITH STATIONARY BED

When the flow rate is below the critical velocity, the coarser solid particles deposit at the bottom of the conduit and a stationary bed is formed with a slow increase in the stationary bed. In the stationary bed, there will be particles on the top of the bed and these are transported as a separate moving layer. High pressure is necessary to cause flow in the stationary bed. With a stationary bed there is the possibility of pipe blockage.

2.3.0 Pipe Flow of Slurries

After gathering some idea of the various flow regimes for slurry flow we now study the flow pattern and nature of slurry flow in different piping types.

2.3.1 SLURRY FLOW IN A HORIZONTAL PIPE

In all practical situations it is not possible to get solid particles of uniform size. In real life there will be a combination of heterogeneous and homogeneous flow regimes. This means that there will be combined homogeneous and heterogeneous slurries being transported, i.e., a part

consisting of fine particles transported as homogeneous flow, while the balance is heterogeneous flow. Depending on the flow velocity there will be settling of different layers that contain different-size particles due to gravity acting perpendicularly to the flow, which results in the coarser denser particles settling as the carrier fluid cannot suspend/lift those particles. Therefore, in a horizontal pipe, there will be a concentration gradient. Two-phase vehicles are deployed for the analysis of the system. In this method, the top part comprises mainly fine solids for homogeneous vehicle mainly comprising fine particle concentration and size distribution and this is uniformly distributed across the pipe. The remaining suspension is in the heterogeneous phase. The pressure loss is the sum of pressure loss due to the homogeneous phase and heterogeneous phase carried out by the vehicle [9].

2.3.2 SLURRY FLOW IN A VERTICAL PIPE

The general recommendation is to maintain the minimum flow velocity at twice that of the settling velocity. Therefore, with a known setting velocity it is possible to estimate the maximum possible slip and effect for variations in solid concentration [9]. It is important to note that when the operating velocity falls below the value required for fluidizing, then there could be a plugged line. When the operating velocity is above the minimum velocity, there will be no formation of bed, however there could be redistribution of particles. There will be no concentration gradient. Therefore, the important velocity parameter can give rise to plug flow, slug flow, and annular flow, etc.

2.3.3 SLURRY FLOW IN AN INCLINED PIPE

Inclined slurry flow is more complex than either horizontal or vertical slurry flow as separation and slippage of phases occur simultaneously [10]. Critical *slope* determination is one of the most important issue so as to avoid pipe blockage, etc.

With this the general discussions on slurry flow come to an end. We now look into the issues from an instrumentation point of view for slurry flows.

3.0.0 INSTRUMENTATION IN SLURRY FLOW MEASUREMENTS

It is extremely difficult to predict any particular type of flow characteristics for slurry flow. The slurry flow characteristics of different industries are quite divergent in nature. Therefore, flow measurement of slurries is always one of the most challenging issues for control and instrumentation engineers. Mining slurries are quite common, however there are a wide variety of other slurries, such as red mud slurry from alumina plants, cement slurry in oil and gas applications, sewage, paper pulp slurry, fly ash slurry from thermal power plants, etc. Apart from these, there are varieties of complex fluid flow measurements in food and beverage industries such as hot chocolate, mayonnaise, fruit juice, ketchup, etc. Also, there are complex fluids like paint. So, on one hand there are varieties of flow-metering principles, and on the other hand there are slurries with many different guises pertinent to various plants. Also, there are many complex fluids whose rheological characteristics are also so diverse that it is difficult to get a suitable flow-measuring device for them. In this section the application details of various instruments used for slurry flow and other complex fluids shall be covered. There is another term called fluid noise, which is more relevant with slurry. The following are some fluid noises created by fluid itself when in contact with the pipe and meters; this is in addition to the electrical noises normally encountered in flow measurements from the surrounding industrial environment. The following are fluid noises caused by the fluid itself found in slurry and multiphase flow measurements:

- Slurry noise generated by the collision of solid particles (as applicable) with the electrode/measuring part;
- Flow noise generated by the friction between the fluid and pipe wall/liner;
- Noise generated by a sudden change in the conductivity, mainly for EMFM.

3.0.1 METER TYPES

From experience, as well as from various literature studies, it has been found that mainly

the categories of flow-measuring instruments listed below are used in flow measurements of slurries and complex fluids. In a complex fluid it is not possible to consider all types of fluid, instead fluid flow for food and beverages like chocolate, mayonnaise, etc. have also been considered and in industrial side paints, oil, mud, etc.

1. **DP method:** Segmental Venturi, wedge, or elbow type.
   - *DP type—Wedge type:* Wedge flow meter/elbow type (with DP/multivariable transmitter used for slurry applications). *Since wedge type flow meters have not been covered in Chapter II, in this chapter they are detailed in Section 5.0.0.*
2. **Positive displacement (PD) meters:** Mainly for complex fluids like paint, hot chocolate, mayonnaise.
3. **Turbine flow meters:** Specially designed for slurry application.
4. **Ultrasonic flow meters:** for slurry application.
5. **Mass flow meter/Coriolis meter:** Used for both slurry and complex fluid applications.
6. Cross-correlation type flow measurement.
7. **Vortex:** Conditionally can be used for high slurry flows.
8. RADAR type return mud flow sensing shall be covered also.

Each of these measuring principles has some advantages or disadvantages in measurement.

None of the above principles are unique enough that they can be deployed for the measurement of slurry flow. As stated above, each of these principles has some advantages and disadvantages; important meter types have been compared in Table VII/3.0.1-1.

TABLE VII/3.0.1-1 Comparison of Various Slurry Flow-Measuring Principles

Flow Meter Type	Advantages	Disadvantages	Remarks
DP method	1. Lower cost 2. Easy to understand and interpret 3. Easy installation more vendor participation	1. Nonrecoverable pressure loss is high 2. Wear of flow element due to slurry abrasion, requirement of maintenance 3. Wear of DPT sensing diaphragm	
PD meters	With sanitary enclosure well suited for food and beverage industries, especially for handling highly viscous fluids like mayonnaise	Moving parts hence maintenance prone	
Magnetic flow meter	1. Nonintrusive, independent of fluid rheology, density, temperature 2. High accuracy	1. Higher initial cost Requirement of minimum conductivity 2. Accuracy and stability depend on type of excitation 3. Sensitive to magnetic noise from other nearby equipment	Not suitable for slurry containing ferrous material

Continued

TABLE VII/3.0.1-1 Comparison of Various Slurry Flow-Measuring Principles—cont'd

Flow Meter Type	Advantages	Disadvantages	Remarks
US type	**1.** Noninvasive **2.** Nonintrusive **3.** No pressure drop **4.** External clamp on mounting; can be used in dirty fluid **5.** Higher accuracy	**1.** Sensitive to velocity profile **2.** Sensitive to air bubbles; common in slurry **3.** High capital cost **4.** Sensitive to solid concentration **5.** Sensitive to gap between metal and lining	
Coriolis	**1.** High accuracy **2.** Independent of flow profile, pipe line pressure, and temperature **3.** Low maintenance cost	**1.** High capital cost **2.** Limited pipe size **3.** Pressure restriction **4.** Pressure drop **5.** Bent tube may foul	
Cross-correlation	**1.** Simpler construction with electrical resistance tomography solid distribution can be ascertained	**1.** Not suitable for low solid concentration and fine particles	

3.0.2 METER SELECTION GUIDE FOR COMPLEX AND SLURRY FLOWS

Flow meter selection would be very easy if there were not so many variations in fluid properties. Unfortunately, this is not the case. In reality there are too many factors influencing the final choice of flow meter for an application, especially for complex and slurry flows. Different slurries have different properties which are responsible for creating noise in flow measurements. Some of the common slurry applications are listed here:

- Coarse slurry (mining industry);
- Pulp with long fibers (paper industry);
- Sewage sludge with more 7% solids;
- Chemicals in the slurry (not mixed properly);
- Bubbling air/gas;
- Inhomogeneous liquids in general.

The importance of understanding the effects of these fluid behaviors in meter selection can never be overestimated. Flow meter selection is mainly guided by the following points (* mainly applicable for slurries):

- Flow profile;
- Flow velocity;
- Solid content and solid property;*
- Chemical composition of fluid/carrier fluid;*
- Liner selection;
- Electronic system.

Of all these factors the flow profile is probably the most important factor because it is influenced by velocity and viscosity. Therefore, this is where the discussions start.

1. **Flow profile:** In the majority of the cases of complex and slurry flows, non-Newtonian behaviors are predominant. As stated earlier, in cases of non-Newtonian flow there is no relationship between pressure and resistance, and so it is very difficult to predict flow behavior. Also, in some cases the flow pattern may change with time and as a result of changes

in the shear force inflicted by resistance from the pipe walls. Also, based on the Reynolds number, the flow may be laminar, transitional, and turbulent. From the discussions in earlier sections it is clear how such conditions affect flow behavior. As flow profile is a function of velocity and viscosity it can better explain the way in which the flow will behave. In this connection Figs. I/1.2.2-3 and I/1.1.2-7 may be referenced. The known flow profile could be the first step towards the selection of a flow meter. In flow profile the major factor is viscosity, which offers the resistance to flow. In the case of Newtonian flow it is constant, whereas in non-Newtonian flow it is not. The degree to which the fluid resists flow in turn affects the velocity of flow. If there is flow profile disturbance, it is most likely that it will force solid particles towards the wall causing abrasion. Therefore, selection depends on how much the flow meter can tolerate profile disturbance.

2. **Velocity:** As stated above, flow profile includes both the flow velocity as well as the viscosity of the medium. Therefore, if the profile is changed there will be a direct effect on the velocity. If there is a high flow velocity of abrasive liquid then there will be higher wear. In order to avoid abrasion it is recommended that the flow velocity be kept lower so as to increase the life span of the meter. However, in the case of slurry it also depends on the slurry settling velocity and in some cases flow velocity below 4 m/s may settle to cause blocking of pipeline [11]. Thus one has to make a balance between the two opposing criteria to get better results.
3. **Solid property and content:** For slurry flows Solid property and contents are important parameters for the selection of a flow meter. In this connection the discussion in Section 2.0.0 may be recalled. Depending on the chemical and mechanical nature of the slurry encountered in various processes the solid concentrations may vary from a few percent to up to 70%. When the percentage of solids is too low standard meters suitable for the application may be deployed, whereas if the percentage is too high then it is suggested to use flow meters especially designed for slurry applications. In fact, of the various types of flow meters indicated above, most have a special instrument meant for slurry application. Similarly, if the solids are fine and uniformly mixed in carrier liquid it is easier to measure the flow. In contrast, if the solid contents are coarse in nature it is rather difficult to measure, so instruments meant for slurry applications should be used to combat the slurry noise. Solid size, as well as shape and nature, determine the abrasiveness of the slurry. Based on abrasiveness the liner and flow meter internals are chosen. Therefore, the liner material or internal material is major consideration regarding the abrasiveness of the slurry [11].
4. **Chemical composition:** Slurries from pulp and paper industries, the mining industry and many other industries have chemicals that are very corrosive in nature. Naturally, soft liner materials may not be suitable for corrosive applications. A ceramic liner is often a good selection for chemicals with a high abrasion effect and that are corrosive in nature. Ceramic is also known to be sensitive to mechanical shock and severe temperature changes, which can make the liner crack [11]. Also, if there is settlement of solids and slurries are not well mixed then there will be a bad signal-to-noise ratio.
5. **Liner selection:** The abrasive and corrosive nature of fluid, along with harsh requirements for cleaning and sterilization in the food and pharmaceutical industries, have given rise to a number of liners and liner technologies [11]. So, while selecting the meter it is important to select the proper liner suitable for the specific application. No single liner technology can be used for the entire range of flow and meter sizes.
6. **Electronic unit:** As stated earlier, on account of improper mix of solids and carrier liquid,

there will be variations in the signal-to-noise ratio. After selection of the proper flow meter it is also important to select proper transmitters with a suitable electronic filter. Selection of the meter based on good noise filtering is important so that suitable stable output is available from the transmitter.

The above discussions would help in selecting a flow meter for a specific application. Now a brief discussion will be presented on the various kinds of flow meter types discussed above from their application point of view with special reference to complex and slurry flow.

3.1.0 Flow Meter Applications in Complex and Slurry Flows

In this section discussions will be presented on various types of instruments discussed earlier and used for the measurement of flow in complex and slurry fluids. These instruments have already been covered in previous chapters in this book (with the exception of wedge flow elements, which will be covered in Section 5.0.0 in this chapter), so, only the required details will be covered here. For the basics of these instruments the respective chapters may be referenced. We start the discussions with the DP cell use in slurry flow.

3.1.1 DP METHOD IN SLURRY FLOW

It is not uncommon to encounter the problem of transportation of a mixture of liquid solid, liquid gas, or liquid carrying different concentrations of sediments over a long distance. Of the many methods of flow measurements for complex and slurry flows the DP method with the help of various flow-measuring devices is the most common, but with some modifications. Some of these DP methods are discussed below.

1. **Eccentric Venturi:** There are a number of problems created on account of this solid-liquid mixture, because in many cases the diluteness of the solids in the liquid violates the continuums approach in the liquid–liquid flow analysis of conduits [12]. Therefore, a number of modifications are necessary in conventional Venturi meters. The major reasons for such a change include but are not limited to the following:
   - In a horizontal pipe for solid-liquid flow there will be excessive wear at the bottom. Also, a horizontal pipe Venturi meter is subject to severe wear at the converging portion due to increased velocity of the solids.
   - Nonuniform distribution of solid particles causes coarser particles to travel at or near the bottom of the meter and pipeline, which in the long run can cause excessive wear.
   - At low velocity, coarser particles settle at the bottom, causing degradation of flow measurement.

   Therefore, a segmental Venturi, as shown in Fig. II/4.1.0-2B, where there is a flat bottom, could be used for slurry applications. Major data regarding the use of segmental Venturi in slurry applications are available from the literature, as listed below [12]. These points should be taken into account while designing a segmental Venturi in slurry applications:
   - Hasan et al. (1982) carried out an experimental study to analyze the effectiveness of a Venturi meter as a flow-measuring device for slurries. It was concluded that for measurement of slurries density must be used in the flow equation of a Venturi meter. The Reynolds number, slurry concentration, and throat diameter were the same for single-phase fluids and slurries. Also, at lower Reynolds number it is difficult to operate as a critical velocity could be reached. The coefficient of discharge was found to be a weak function of Reynolds' number and found to be increased with an increase in solid concentration. At high Reynolds number (>60,000) for all slurry concentrations and Venturies was about the same as that for single-phase flow.
   - Shook et al. (1982) observed in his experiment that for stratified slurries, the discharge coefficient was higher than that of homogeneous fluids. This effect was

found to be increased by increasing slurry concentration and decreased by increasing the velocity of flow.
- Bharani et al. (1999) carried out an experiment with study of a modified Venturi meter, which was expected to suppress the erosion rate that was caused by the movement of solid particles in a solid-liquid mixture flow in a Venturi meter to analyze the performance characteristics of an eccentric Venturi meter with elongated throat for solid-liquid flows [12].

2. **Wedge flow element:** Another differential pressure-producing element very commonly used in slurry, liquid with suspension, and high viscous flow applications is the wedge. As wedge flow elements find their major use in slurry, so (instead of discussing in Chapter II) they are discussed in detail in Section 5.0.0 of this chapter. Unlike many other differential-producing flow elements, the wedge is rather *insensitive* to Reynolds number, it can sense flow even in a very low Reynolds number, e.g., 500. Some of the major features and application areas for wedges are listed here:
- Rugged and robust design and construction;
- No moving parts;
- Lower permanent pressure loss;
- High-viscous fluid handling capacity;
- Used for liquids with suspension or slurry, and highly viscous liquids;
- Well-proven technology;
- Good accuracy;
- Stable operation in most process conditions;
- Used for highly viscous, corrosive, and abrasive fluids;
- Fluid with low Reynolds number are measured by it;
- Used for slurry and liquid with suspension/entrained solids;
- It can measure bidirectional flow.

3. **Elbow flow element:** Frankly speaking, this is not a flow element, instead pipe elbows are utilized to generate differential pressure for measuring velocity and flow determination. A description and other details on an elbow flow measurement system is available in Section 8.2.0 of Chapter II. Since no additional flow element is used it therefore is of low cost. However, this does not give good accuracy, and from its cost and installation advantages that it is often used for slurry flow applications. Elbow meters in slurry flow measurement are found in the dredging industry, where the greater accuracy offered by a magnetic flow meter or Coriolis meter is not necessary. In the dredging industry, where silt—clay—water mixtures are pumped in the operation, an elbow meter near a centrifugal pump would give quite a reliable guide concerning the relative flow in the discharge system.

After the differential pressure measurement technology (Chapter II and Section 5.0.0 of this chapter) we shall move on to positive displacement meters to see how these can be used to measure complex flows, like chocolate, mayonnaise, yogurt, etc.

3.1.2 POSITIVE DISPLACEMENT METER COMPLEX FLOW MEASUREMENT

In many cases of complex fluid flow, such as in food industries, where there will be flow of very highly viscous fluid it may be with entrained solids and hydrogenated oil (which may solidify at certain temperatures). As found in the food and beverage industries, the PD meter is often found to be a good solution. In chocolate production additional problems come from thick abrasive chocolate, which not only causes a high pressure drop but at times blocks the flow. As is now clear after discussions in Chapter IV, positive displacement flow meters are suitable for high-viscous flow. Let us now examine the benefits and specification specialties of PD in complex fluid flow applications in the following discussions. The basic details on PD meters have already been discussed in Chapter IV, hence for basic details Chapter IV should be referenced. Here specific details of PD for complex flow applications have been enumerated.

Also, out of so many types of PD meters only a few types are suitable to face such harsh

technical requirements. Dual-impeller PD flow meters are often used. These flow meters need to be selected carefully; as slight variations in control can damage the quality of the product, such as texture, etc. Therefore, it is essential that the meter to be used is of high accuracy, to the tune of at least 0.5% AR, along with a high turndown ratio. Meters especially developed for the food industry often offer the same accuracy with a very high turndown ratio, e.g., flow technology (DC-F series) PD meter with high accuracy and turndown ratio of 1000:1. As stated earlier, in most cases meters may have to withstand very high viscosity, possibly up to a static viscosity of 50,000 cP and dynamic viscosity over 7000 cP. On account of batch operation, the line size requirements may vary from, e.g., 6 to up to 80 mm. In many cases in food and beverage industries such flow meters need to have built-in heat tracing so that the flowing fluid does not solidify, e.g., chocolate production. A few features of PD meters include the following.

Designed for sanitary applications:

1. **Accuracy:** 0.5% AR;
2. **Repeatability:** ±0.05% AR or better;
3. **Linearity:** ±0.1% AR or better;
4. **Electronics:** Linearization, output 4−20 mADC or pulse often available with digital communication;
5. **Line size:** 3 up to 100 mm;
6. **Turndown:** Up to 1000:1;
7. **Viscosity range:** Up to 1,000,000 cP+;
8. **Materials of construction:** Normally all 316 SS food grade;
9. **Operating pressure:** 20 bar.

Apart from PD meters, there are a few other meters, such as turbine meters and Coriolis meters, that are also used in food and beverage industries and these are discussed below.

3.1.3 TURBINE METER FOR COMPLEX AND SLURRY FLOW MEASUREMENT

The use of turbine meters in complex fluid applications even in certain cases of the food and beverage industries is not uncommon. However, there are turbine meters which are specially designed and manufactured for use in rugged conditions and very harsh environments, such as highly abrasive, corrosive, slurry, and complex fluids. Here we examine the benefits and specification specialties of turbine flow meters in complex fluid flow applications. For basic details on turbine flow meter Chapter V should be referenced. Here specific details of turbine flow meters for slurry flow and for complex flow applications have been enumerated. Such applications in slurry and complex fluid flow include but are not limited to the following:

1. Water−sand;
2. Mud in oil and gas;
3. Cement slurry;
4. Mud applications;
5. Mud cementing operation;
6. Flowback of treatment fluids.

   These turbine meters for abrasive and slurry applications have special designs that provide durability and longevity of the meter and deliver accurate, reliable results. Specification details of these specially designed turbine meters are as listed here [13,14].
7. **Short specification:**
   - *Process pressure:* 60 bar;
   - *Process temperature:* −73 to 150°C (some design >230°C);
   - *Meter sizes:* 25 m to 100 mm;
   - *Flow range:* around 20 to 11,000 LPM in different spans;
   - *Materials of construction:-*
   - *Meter body:* 316 stainless steel;
   - *Rotor:* 17-4 PH stainless steel/316 SS with suitable coating (nickel plated);
   - *Rotor shaft and bearing:* Tungsten carbide binder less carbide shaft for enhanced corrosion resistance to selected chemicals;
   - *End connection:* Victaulic/WECO union for quick installation;
   - Normally these long-life turbine meters require medium maintenance.

3.1.4 ELECTROMAGNETIC METER FOR COMPLEX AND SLURRY FLOW MEASUREMENT

In slurry flow and some cases of non-Newtonian complex fluid flow measurement, electromagnetic flow meters (EMFMs) have a great role to play. Apart from its use as a single instrument, EMFMs are often used along with resistance tomography instruments in correlation measurement instruments. In slurry flow there is lot of noise where EMFMs show better results in suppressing noises. EMFMs are extensively used in pulp and paper slurries, and mining and metallurgical slurries. However, slurry flow may affect EMFM measurement because of distortion in flow pattern and variations in conductivity and permeability. Normally EMFMs are installed in vertical line in slurry services, to avoid slipping between conductive liquid and nonconducting solids [15]. Another interesting and obvious issue is that the magnetic slurry will affect the magnetic field of the meter. Also, there may be magnetic slurry deposit in the magnetic field area. Therefore, a lower field strength of magnet is often used [15]. Based on slurry characteristics, the amplitude and frequency of the field are decided. We now examine the benefits, applications, and specification specialties of EMFM in slurry applications in the following discussions. Basic details on EMFMs have already been discussed in Chapter V, hence for basic details Chapter V should be referenced. Here, specific details of EMFM for slurry and complex flow applications have been enumerated.

1. **Features:** The following are the major benefits offered by some EMFMs especially designed for slurry flow measurements:
   - Wide range of sizes from DN 15 to DN 1000 (½″ to 40″);
   - Broad range of liner and electrode materials for extreme process media;
   - Available in fully welded construction;
   - Stable and accurate measurement in severe process conditions and harsh environments;
   - Higher slurry noise resistance for accuracy and stability;
   - Benefits of AC magnetic meter systems combined with the stability and performance of pulsed DC technology;
   - Use of dual-frequency excitation system, e.g., ADMAG AXR of YEL;
   - Use of a feed-through capacitor to get better electrical Signal to noise (S/N) ratio and low noise amplifier in signal processing;
   - Use of injection-molded PFA lining;
   - Some instruments offer automatic reading of smart PLUG for easy commissioning;
   - Simple menu operation with multiple-line display;
   - Possible to adjust field characteristics for magnetic slurries;
   - Comprehensive self-diagnostics with self-monitoring and internal simulation;
   - Insertion type EMFMs for slurry application are a good choice. Hot-tap versions are available (e.g., OMEGA insertion type EMFM).
2. **Application:** Application areas for EMFMs include but are not limited to the following:
   - Pulp and paper industry;
   - Alumina plant;
   - Mining industry;
   - High concentrated paper stock;
   - Cement slurry (drilling operation);
   - Heavy mining slurries;
   - Mining slurries with magnetic particles;
   - Low conductive medias $\geq$1 μs/cm (0.1 μs/cm depending on medium).

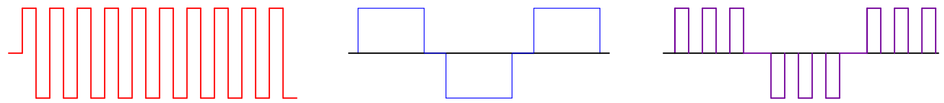
   Now we concentrate on some of the major issues related to specifications needed for use of EMFM in slurry applications. From Section 3.0.0 it can be seen that there are flow noises in the case of slurry flow. One way to get rid of this in EMFM is to use high-frequency AC field excitation. Again, zero stability and accuracy are not good at high-frequency excitation. Zero stability and accuracy are better in the case of DC or low-frequency excitation. Therefore, a trade off needs to be found for

the same. Dual-frequency excitation, discussed in Subsection 3.1.4.4, could be a solution. Here various changes by reputed manufacturers made in EMFM design for slurry and complex fluid applications are discussed. Since these changes have been noted from different manufacturers they will not match any one manufacturer's specification, but have been given here for the reader to judge which is suitable for their own specific application.

3. **Specification:** The following are some of the specifications worth noting for slurry and non-Newtonian complex fluid flow applications:
   - *Size:* 80−900 mm;
   - *Flow velocity:* 0.05−10 m/s;
   - *Excitation:* High-signal pulsed DC and/or dual-frequency excitation;
   - *Liner:* Polyurethane (abrasion-resistant to slurries with small particles); Neoprene (typically applied to water and seawater and Abrasion-resistant to slurries with small particles); Linatx for mining slurries and slurry with larger debris. Injection-molded PFA with retaining grid, e.g., ADMAG AXF of YEL (suitable for red mud, paper plant digester, pulp outlet flow). A ceramic lining with high-purity alumina is a very good lining material for very corrosive and aggressive slurries. A ceramic lining is also offered by a majority of standard suppliers.
   - *Temperature of liners:* Normally −20 to a maximum of 85°C but in some cases like polyurethane it is lower (60°C);
   - *Sizes for liner:* all these liners may not be available for all sizes, so manufacturers should be consulted for the available size;
   - *Electrode:* A variety of electrodes are available, such as 316SS, nickel alloy, tantalum, platinum (80% platinum, 20% iridium), and titanium. A platinum electrode is better suited for fibrous slurry, such as paper slurry. A capacitance type sensing magnetic flow meter with a mirror-finished liner is well suited for red mud applications, e.g., ADMAG AXF of YEL;
   - *Diagnostics:* A high smart diagnostic system is helpful for quick fault detection.
4. **Dual-frequency two-wire EMFM:** During the initial discussions in Section 3.1.4 it was mentioned that with high-frequency field excitation, flow noise decreases but it will not improve zero stability and accuracy. Slurry noise is at low-frequency noise for about 70% of the noise occurring below 15 Hz, so high-frequency 60 Hz excitation allows the EMFM to measure flow accurately [16]. Many thus use DC pulse signals. Dual-frequency excitation, of Yokogawa, has addressed all these issues.

   A high-frequency signal is superimposed on a low-frequency signal, thus one gets a dual-frequency (modulated) signal as shown in Fig. VII/3.1.4-1A. In this connection Subsection 5.3.2.3 and Fig. V/5.3.2-1B may also be referenced. As shown in the table within the figure Fig. VII/3.1.4-1 [17] in the questions that such type of excitation suppresses the noise as well as takes care of temporal changes and better zero stability. Another interesting feature with two-wire EMFM is that it reduces power consumption. Thus two-wire dual-frequency EMFM provides improved efficiency of the signal processing software in order to adopt a dual-frequency excitation method [17]. In order to reduce power consumption, the meter adapts, switching type excitation system as shown in Fig. VII/3.1.4-1B. Thus, in this system the excitation current varies according to the output. The flow rate span of 0%−100% flow rates has been divided into three parts. In each part there are three excitation current levels which increase with flow rate or output levels and the excitation currents are switched from one to other with an increase in output. Calibration is an important issue here. According to the experts at YEL

(A)

TYPES	HIGH–FREQUENCY EXCITATION	LOW–FREQUENCY EXCITATION	DUAL FREQUENCY EXCITATION
WAVEFORM			
WAVE FORM	50Hz	5–20Hz	12.5 , 75Hz
NOISE IMMUNITY	HIGH	LOW	HIGH
STABILITY	LOW	HIGH	HIGH
ACCURACY	LOW	HIGH	HIGH

(B)

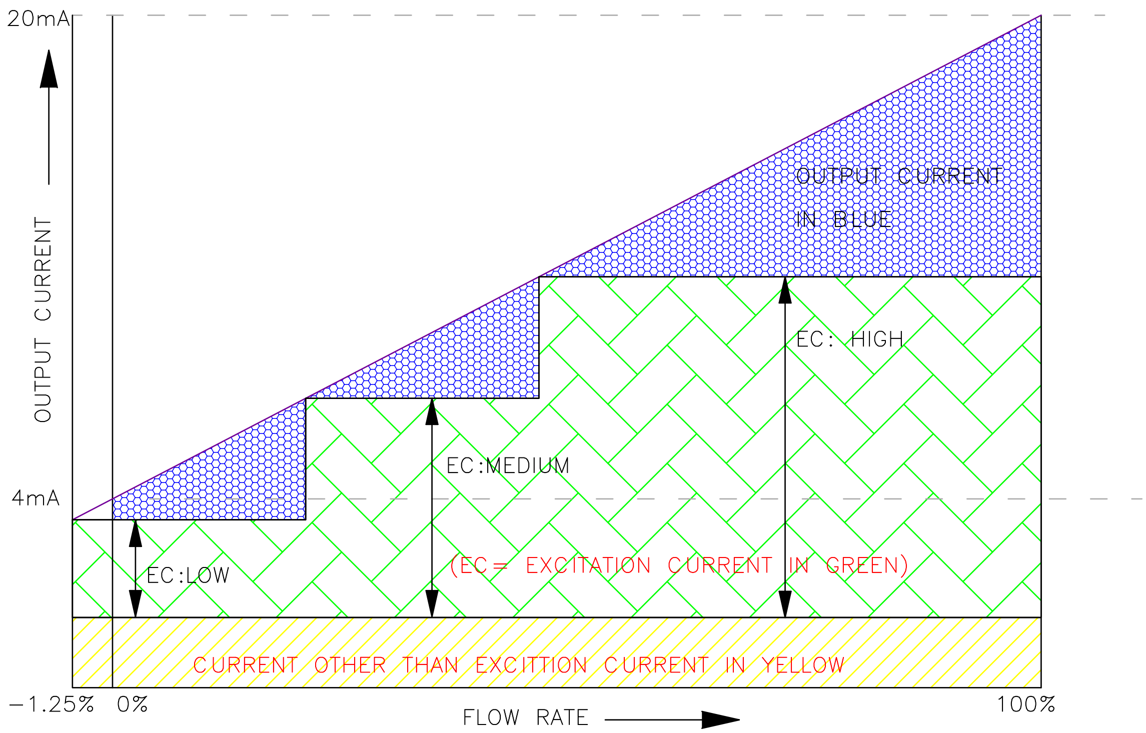


FIGURE VII/3.1.4-1 Slurry flow EMFM excitation. (A) Dual-frequency excitation methods. (B) Excitation current switching. *Both figures have been adapted from Y. Aoyama, F. Sugawara, T. Shimura, Y. Kaneko, H. Noda, A. Yasumatsu. Two-Wire Magnetic Flow meter. Yokogawa Technical Report English. Edition Vol. 53 No.2; 2010. https://www.yokogawa.com/rd/pdf/TR/rd-te-r05302-004.pdf. Courtesy: Yokogawa Japan.*

"Although calibration time is required to prevent errors caused by the small magnetic circuit nonlinearity due to the excitation current switching, flow calibration with actual fluid is performed with each excitation current" [17]. In order to improve the performance and for low power consumption, the meter incorporates a number of changes

compared to conventional EMFMs. Some of these are listed here:
- Low noise amplifier;
- Feed-through capacitor for electrical noise rejection;
- Increased signal electromotive force;
- Low-noise electrodes;
- Mirror-finished lining surface.

5. **Other noise elimination:** It is clear that for slurry flow measurement by a magnetic flow meter, slurry noise is an important issue. Dual-frequency excitation is one of the possibilities. Some other manufacturers adapt different methods to achieve the same results. EMFMs operate at fixed (set for dual frequency) coil drive frequency. Suppliers such as Rosemount select the frequency based on physical parameters such as velocity, solid content, viscosity, fiber length (where applicable), etc. Digital signal processing to get better performance is another way of looking at the issue. Refer to Section 4.4.4 in this chapter also for further discussions.

   The discussions on EMFM end here, and we take up another important flow meter type: the ultrasonic flow meters, especially Doppler type ultrasonic flow meters, are extensively used in slurry flow applications. We now investigate these for slurry and complex fluid flow.

3.1.5 ULTRASONIC METER FOR COMPLEX AND SLURRY FLOW MEASUREMENT

Basic details on ultrasonic flow meters have already been discussed in Chapter V, hence for basic details Chapter V should be referenced. Here, specific details of ultrasonic meters for slurry and complex flow applications have been enumerated. In many cases ultrasonic flow meters are specially developed for slurry flow, they are widely used in ash slurries in power plants. Some manufacturers develop these meters for specific uses, e.g., the Greyline SFM 6 (specifically developed for ash in coal-fired power plants). Apart from these, there are a few other slurry applications where the meters are extensively used. We now look into the features, applications, and specification details for ultrasonic flow meter.

1. **Features:** The following are the basic features with special reference to slurry applications:
   - Easy intuitive setup;
   - Noninvasive and nonintrusive;
   - No pressure drop;
   - Being external, there is no chance of being damaged by abrasive fluid;
   - Easy installation and removal without disturbing the process.
2. **Application:** The application areas of US meters include but are not limited to the following:
   - Fly ash slurry;
   - Bottom ash;
   - Limestone slurry;
   - Copper pulp;
   - Gypsum slurry;
   - Fracturing sand in oil and gas;
   - Sludge raw sewage;
   - Chemical and acid solvents;
   - Viscous liquids;
   - Lubricating oils;
   - Crude oil;
   - Liquid with suspended solids.
3. **Specification:** A few pertinent issues of US meters in connection with slurry flows are as follows:
   - *External use in pipe sizes:* 12−4500 mm;
   - *Pipe materials:* CS/SS/DI/Cu/FRP/ABS/PVC;
   - *Fluid speed:* 0.075−12 m/s;
   - *Accuracy:* 1.5%−2% AR;
   - *Alarm and control relay:* provided;
   - *Enclosure:* IP65;
   - *Solid:* Minimum size >100 μm and concentration >70 ppm;
   - *Accessories:* Signal cable, mounting bracket;
   - *Intrinsic safety (IS):* Possible;
   - *Filter:* Noise-suppression filter for slurry.

Mass flow meters, especially Coriolis meters, are frequently used for slurry flow measurements also.

3.1.6 MASS FLOW METERS FOR COMPLEX AND SLURRY FLOW MEASUREMENT

As mass flow meters are not influenced by physical factors, such as pressure, temperature, density, viscosity, and conduction, they can be used for mass flow of any fluid, i.e., oil, gas, grease, alcohol, detergent, wine, chocolate, and similar media. Also, mass flow meters find their applications in slurry flow measurements. However, on account of the higher pressure drop, mass flow meter use in highly viscous fluids may be limited. In cases where there are fluids with air bubbles, the meter may be affected by these air bubbles with a dampening effect on oscillations. For inhomogeneous materials, vertical installation of the device, especially for low flow rates, is highly important. However, there will not be many changes or modifications from the main meters for slurry applications, therefore the mass flow meter detailed in Chapter VI may be referenced with special attention for the selection of materials of construction and pressure drop.

The vortex is another meter often used in flow measurements in slurry and complex fluids.

3.1.7 VORTEX METER FOR COMPLEX AND SLURRY FLOW MEASUREMENT

Vortex meters with piezoresistive sensors are often used for nonabrasive slurry flow measurements. These meters can give an accuracy of 1% AR. These meters are generally available in various end fittings, with sizes ranging from 6 up to 100 mm, these meters have high side viscosity limitations. Some of these meters offer a turndown of 10:1. For basic details of the flow meter, Chapter V may be referenced.

3.1.8 SLURRY FLOW MEASUREMENT AND ELECTRICAL RESISTANCE TOMOGRAPHY

In this section brief discussions are presented on slurry flow measurement issues and how electrical resistance tomography can be used for slurry flow measurement.

1. **Slurry flow measurement:** Slurry is essentially a mixture of solid and liquid. The physical characteristics of slurry do not depend on carrier liquid alone nor on solid property alone. *Slurry physical characteristics are a function of a number of parameters such as the following:*
   - Size, concentration, and concentration distributions of solids in carrier fluid;
   - The line size;
   - Flow regime based on Reynolds number, i.e., degree of turbulence;
   - Physical parameters like temperature, pressure, and viscosity of the carrier.

   As it is important in many industrial applications, including the transportation phenomenon of the slurry, it is essential that proper study of the same be carried out. As stated earlier, slurry is a mixture and a kind of multiphase flow. In multiphase slurry flow, there are numerous flow regimes which are a function of *flow geometry* (size and shape—as stated earlier) and *orientation* (vertical, horizontal, and inclined), flow direction in vertical or inclined flows (up or down), phase flow rates [18], and other physical properties already discussed. Therefore, issues in the case of multiphase are much more complex when compared with single-phase flow measurements because there may be some local issues, even if the flow is steady or there may be a change in distribution or velocity of phase etc. In slurry flow measurement there is use of a tomography line with many other multiphase measurements discussed in detail in Chapter IX. In general, in tomography, the desired local values of the respective properties are reconstructed mathematically from a certain number of integral measurements [19]. Electrical impedance tomography (EIT) is one of many types of tomography discussed at length in Chapter IX. There are two types of EIT: one where capacitance is the measuring parameter and another where conductance (hence resistance) is the measuring parameter. In slurry flow measurement, electrical resistance

tomography (ERT) is used in correlation type measurement (normally in conjunction with a magnetic flow meter).

2. **Electrical resistance tomography:** The purpose of electrical impedance methods is to establish component fraction measurements by characterizing the fluid flowing in the measurement section of the pipe as an electrical conductor [20]. In EIT, the properties of the fluid mixture are measured in terms of conductance and capacitance, i.e., impedance across the pipe diameter is determined to find the component fraction. In tomography, when electrical conductance is utilized for measurement, it is ERT. In many places electrical impedance tomography (EIT) is synonymously described as electrical resistance tomography (ERT), but this is incorrect. Electrical resistance tomography is a branch of electrical impedance tomography (discussed at length in Chapter IX) in which the conductivity of an electrical property is exploited to image the conductivity distribution in a two-phase slurry. A schematic of a typical ERT has been shown in Fig. VII/3.1.8-1. Therefore, ERT can be utilized to investigate and monitor any process where the *main continuous phase* (carrier fluid) possesses a minimum conductivity for measurement and the other phases and components (e.g., solids) have differing values of conductivity. Like body scanning, ERT develops a cross-sectional image to highlight the distribution of electrical conductivity of the contents within the conduit with the help of electrodes at the boundary of the pipeline.

In an ERT system, the conductivity is measured by injecting a known or controlled electrical current into the flow, and then the voltage difference between the remaining electrode pairs, along an insulated section of the pipe, according to the measurement protocol, which is a predefined one (developed prior to the measurement program). The current can be injected by contact electrodes or in a noncontacting mode by coils. A single measurement set consists of a good number of voltage measurements—the exact number depends on the predefined protocol mentioned above. For known distance between electrodes the measured resistance can be converted to

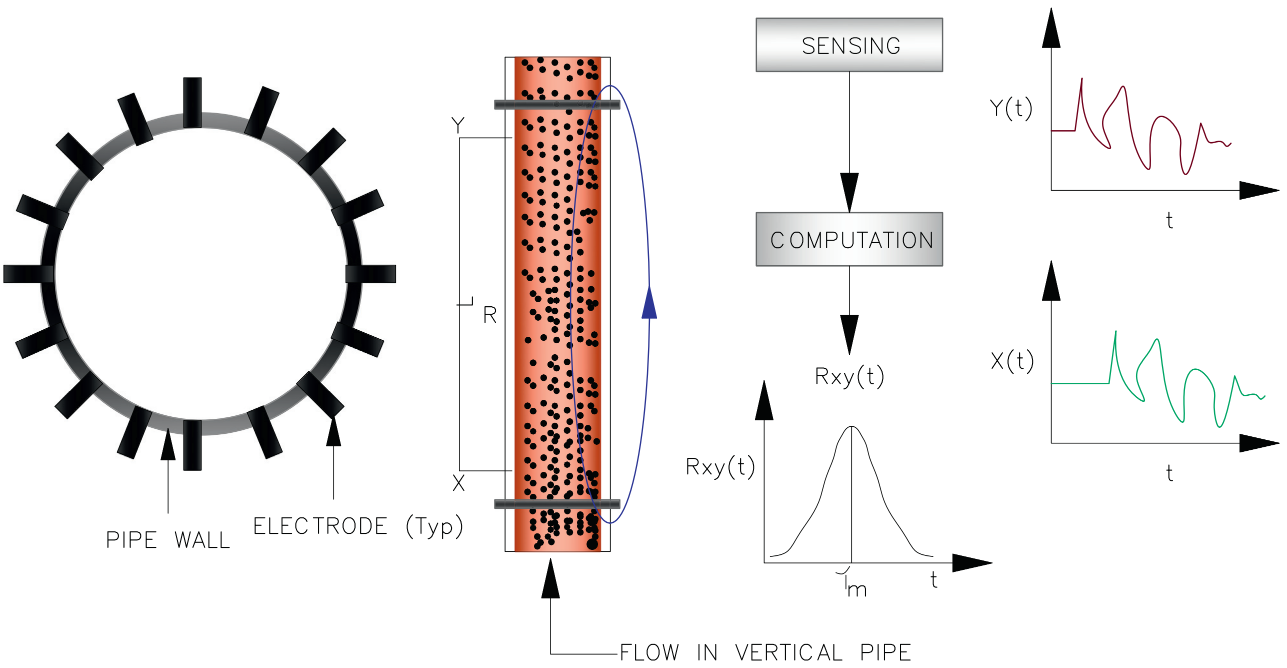


FIGURE VII/3.1.8-1 ERT schematic.

conductivity. Typically there are 16 electrodes built in-house on the periphery of the pipe as shown in Fig. VII/3.1.8-1 (leftmost one).

3. **Measurement:** After theoretical discussions, we now attempt to understand physically the operation. For this we refer to the middle figure in Fig. VII/3.1.8-1. In an actual slurry flow there may be a fluctuation of conductivity on account of the conductivity difference between the carrier fluid and solids. To understand this let us consider two conductivity sensors located at X and Y at a known axial distance of L. On account of random changes in composition, let the conductivity signals be x(t) and y(t), measured at X and Y as shown. When x(t) and y(t) are plotted against time the patterns would be similar, only shifted in time due to the time of traveling between two sensors. If the bulk average velocity of bulk slurry is v_m and there is no fluctuation during traveling between from X and Y, then one can write $X(t) = Y(t + \tau)$ when τ is the delay. However, "the turbulence in the pipe flow causes the fluctuation patterns to be convected with velocity dependent on the radial pattern and Reynolds number and to be dispersed due to turbulent diffusion" [15]. As result of this individual fluctuations will be influenced by distribution pattern. Therefore, the distribution for delay can be found from the general correlation. Also, on account of the distribution pattern and such fluctuation, resistance will be a function of time, i.e., changes with time. Therefore, measured resistance R_{xy} between X and Y will be given by:

$$R_{xy}(t) = \frac{1}{T}\cdot \int_0^T X(t)\cdot Y(t+\tau)dt \quad \text{(VII/3.1.8-1)}$$

here T is the sampling period and τ is the delay time. If for a delay time τ_m Eq. (VII/3.1.8-1) is maximized, then the mean velocity v will be given by:

$$v_m = L/\tau_m \quad \text{(VII/3.1.8-2)}$$

Thus we find that by measuring the resistance between the electrodes correlation can be established as shown in the right-most fig in Fig. VII/3.1.8-1. An image reconstruction algorithm processes the voltage measurements to determine the electrical conductivity distribution. From ERT the distribution pattern and bulk average velocity are determined and can be used in correlation measurement with another flow-measuring instrument, e.g., EMFM, to determine the exact slurry flow as discussed in the next section.

3.2.0 Cross-Correlation Measurement in Slurry Flow

Since EMFM introduces practically zero pressure drop and can provide a fast response to changes in the flow, EMFM can be used in the measurement of flow of slurry as the main volumetric flow determination. However, on account of the complexity of multiphase flow in solid slurry transportation, it is difficult to accurately measure solid concentration and flow rate using a conventional electromagnetic flow meter alone [19]. Therefore, a secondary sensing method, electrical resistance tomography (ERT), is used for a cross-correlation method of flow measurement in slurry. As discussed above, ERT is used to predict solid concentration, disperse phase velocity, and flow regimes in slurry flows (possible for vertical and horizontal flows). Therefore in the cross-correlation method both ERT and EMFM are used. At this point it is necessary to define the term "slip velocity." Except in vertical downward flow, in a liquid–solid two-phase flow, the liquid phase moves much faster than the solid. The difference in the in situ average velocities between the liquid and solid phases will result in a very important phenomenon: the "slip" of one phase relative to the other, or the "hold-up" of one phase relative to the other. This makes the in situ volume fractions different to the solid loading volume fractions [19]. From a study of

literature it was found that Bevir (1970) established a relationship between the measured potential difference of electrode and single liquid flow rate with the homogeneity factor based on the conductivity distribution. This helped in estimating the mean volumetric fraction of solids through imaging (using the Maxwell relationship). In a computing circuit the data from EMFM and ERT are correlated to establish the corrected volume flow rate of slurry, taking into account the solid particle distribution in the conduit. Thus, the result from EMFM needs to be correlated and corrected with ERT results to obtain better accuracy, especially in slurry flow measurement for nonhomogeneous flow. Slip velocity and flow patterns play a great role in measurement accuracy.

3.3.0 SONAR in Multiphase Slurry Flow Measurement

As discussed earlier in Section 9.0.0 of Chapter V, SONAR also measures volume fraction and volumetric flow necessary for slurry flow measurement. The discussions presented here will supplement the discussions in Section 9.0.0 of Chapter V. The velocity measurement by tracking eddies has already been described in Chapter V and hence is not repeated here. In the case of slurry measurement there may be some issues arising from the use of lining materials used in pipes for slurries. However, the manufacturer claims that the instruments have been used for different liners with many kinds of steel pipes as well as nonmetallic pipes like PVC, HDPE, and fiberglass to name a few. The high noise level prevalent in industrial environments is another big issue. However, according to the manufacturer this can be isolated and the issue can be addressed with the help of an array processing algorithm.

In an industrial environment there are naturally generated low-frequency acoustic waves with wavelengths much longer than the entrained gas bubbles [21]. These waves travel in the pipe's axial direction. They can propagate in a downward direction (or both ways).

A similar array of passive sensors as already discussed in Section 9.1.0 of Chapter V can be deployed to measure the average axial velocities of a collection of acoustic waves. Also, similar array processing algorithms can be used to interpret the signals. Acoustic waves are traveling pressure waves that cause pressure changes inside the pipe. Such pressure changes in the form of strain are tracked in the similar manner as is used for tracking eddies. In multiphase fluids, e.g., slurry or a gas mixed with a liquid, the acoustic velocity can be used to determine the amount of entrained gas (gas void fraction) when the gas is in the form of bubbles that are well mixed within the liquid or slurry [21]. In this manner, with the help of array processing algorithms it is possible to get the volume fraction for accurate slurry flow measurement.

To complete these discussions, application of various flow instruments in different slurry and complex fluid flows commonly encountered in process and industrial plants will be discussed in the next section.

4.0.0 INSTRUMENTATION FOR SELECTED SLURRY AND COMPLEX FLOW APPLICATIONS

In the discussions so far we have basically gone through the theoretical aspects of slurry and complex measurements. Discussions have been presented on basic physics and fluid mechanics for slurry and complex flow. Also, principles of complex and slurry flow through various instrument types and associated modifications for measurements have been covered. In this section some selected slurry and complex flow applications frequently encountered in process and industrial plants are covered so as to understand the instrumentation applications as well as the characteristic specialties associated with them. It is

impossible to cover all slurry and complex fluid applications, however the majority of common industrial applications are included. These shall cover the following areas:

1. Ash slurry (power application);
2. Cement slurry;
3. Drilling fluid/mud;
4. Pulp and paper slurry;
5. Red mud slurry;
6. Complex fluids in food and beverages.

The discussion starts with the ash slurry flow application.

4.1.0 Ash and Limestone Slurry Flow Measurement in Coal-Fired Power Plants

Ash slurry transportation is mainly related to coal-fired power plants, which account for almost 40% of total worldwide power generation. In the USA >50% of power generation is from coal, similarly, in India and China >75% and >70%, respectively, of power generation comes from coal. These figures clearly show that there is the possibility of high air pollution from fly ash, which in a dry bottom boiler can be as high as 80%.

4.1.1 ASH-HANDLING MODES AND FLOW BEHAVIOR

It is not that dry ash handling modes are not there, but in and many cases fly ash is transported in wet form. There is therefore a requirement for ash slurry handling. In view of this, the importance of the characteristic features of ash slurry flow and ash slurry flow rate measurement cannot be overestimated. We now look at details of ash slurry transportation for which it is important to get some idea of the slurry characteristics of ash slurry. The major characteristics of ash slurry mainly include the following:

1. Settling properties;
2. Process of transportation of fly ash;
3. Flow behavior of ash slurry.

Of these flow behaviors the slurry flow rate measurement in ash slurry is most important. From Section 2.2.0 in this chapter, we have seen that when a solid—liquid mixture is conveyed through a pipe, different regimes and conditions of flow may be encountered, depending on the properties of the solids, carrier fluid (water), and the geometry and characteristics of the pipeline. The different hydraulic flow conditions of slurry are homogeneous, intermediate, and saltation flow, as already described. The velocity of transportation is very important for various flow regimes. In coal-fired thermal power plants there can be more than 30 flow meters to measure ash slurry flow.

4.1.2 ASH SLURRY AND LIMESTONE FLOW METER

In most cases Doppler ultrasonic meters are deployed to measure the velocity in ash slurry and use suitable software to compute the flow, taking into consideration various conditions of slurries. But *why are Doppler US flow meters so popular?*

In order to get the answer we need to look into the background. As people are concerned about pollution as per "clean air regulations," it is necessary to bring down the NO_x and SO_x levels below the specified levels. A limestone slurry is typically sprayed into the flue gas stream to remove SO_x. For further details, Ref. [22] may be referenced. The limestone slurry is abrasive so in-line flow meters are not good choices. In contrast, Doppler US flow meters work nicely when there are solids present in the fluid conveyed. Also, Doppler flow meters are noninvasive and nonintrusive, and so Doppler US flow meters are an ideal choice for slurry flow measurement. Noncontacting Doppler flow meters can be used both on the fly ash slurry supply lines and recirculation slurry lines.

As this is noninvasive, there is no need to shut down or disturb the meter installations and removal. These meter sensors are mounted

from outside in different pipe sizes and materials. These meters may have an integral transmitter section or can be mounted in a safe place at a distance. Normally an accuracy of around 2% AR is available from the meter. Most offer associated data-logging facility and communication facilities for remote transmission via fieldbus, etc. This is in addition to normal 4—20 mADC/pulse output.

4.2.0 Cement Slurry Flow Measurement

Cement is widely used for construction purposes, as well as in industry and for other purposes, for example, cementing in drilling operations, a major application of cement slurry. Nowadays the emphasis is put on the quality of cement. Cement slurry meant for drilling is especially designed based on a number of issues. A list of such major issues is as follows:

- Well depth, diameter, and casing sizes;
- Mud density used;
- Bottom hole—static temperature (BHST), circulating temperature, and pressure;
- Properties of cement in the lot available;
- Additives and their properties;
- Water quality at site.

Similarly, the properties of cement are extremely important for flow measurement. Major cement properties are as listed below:

- Rheology;
- Slurry density;
- Thickening time;
- Strength of retrogression and compression;
- Fluid loss control;
- Feed water content.

In most cases specially designed electromagnetic flow meters and specially designed turbine flow meters that are used for this purpose. In this connection a turbine flow meter specially developed for cement slurry could be used. Details regarding the technical details of turbine meter have already been described in Section 3.1.3, which may be referenced. Also, there are specially designed EMFMs meant for cement slurry applications discussed in Section 3.1.4. These EMFMs have an accuracy of up to 0.2% AR, whereas the same for a turbine meter is nearly 1% AR. However, the turbine meters with WECO connection are better suited for this application. Normally flow meters are suitable for use in temperatures up to 180°C, but with a rubber lining in EMFM the temperature is limited to around 130°C. These flow meters (EMFMs) are available in sizes from 15 up to 3000 mm to cater to velocity ranges from 0.1 to 5 m/s. A variety of electrode materials and lining materials are available for the EMFMs meant for cement slurry. Paddle wheel flow meters discussed later in Section 4.3.4 are also used for cement slurry applications. Ultrasonic flow meters (Doppler type) are often used in the measurement of concrete slurry, another kind of cement slurry. As Doppler meters are noninvasive and nonintrusive they find good applications in concrete flow measurements.

4.3.0 Drilling Fluid/Mud

A drilling mud is a complex fluid comprising a multitude of additives depending on the drilling method employed and the type of reservoir to be drilled. A good understanding of the effects of drilling fluid rheology is a very important aspect of selectively designed fluids, which could cater to various requirements of drilling and could encounter the difficulties in oilfield drilling operations. Prior to starting discussions on drilling fluid measurement it is better to have clear idea about various mud types, the purposes of drilling mud, and types of drilling, so that the reader has an idea about the requirements of flow measurements in drilling operations and the associated complexities. Also a few drilling terminology detailed in Fig. VII/4.3.0-1 are important. As the drilling process is a rather complex process, it is suggested for the reader to go through a *basic drilling process* from any standard book on the drilling process to get an idea about the measurements involved.

BHP: *BHP represents the bottom hole pressure and is defined as the pressure measured at the bottom hole. This is a static pressure calculated on the basis of multiplication of mud weight (pound/gallon as per Schlumberger glossary) with vertical depth and conversion factor.*

ECD: *Effective circulating density has been abbreviated as ECD. This is the effective density exerted by the circulating fluid against the formation taking into account the pressure drop in annulus above the point of measurement*

FIGURE VII/4.3.0-1 Drilling terminology.

4.3.1 MUD FLUID CLASSIFICATION

Drilling mud can be broadly classified into water-based mud (WBM), oil-based mud (OBM), synthetic-based mud (SBM), emulsions, invert emulsions, air, and foam fluids.

1. **Water-based mud (WBM):** WBM uses water/brine as the base fluid, where the drill cuttings can be disposed of easily. WBM takes a synthetic polymer/biopolymer or crosslinked polymer additive as a viscofying agent. Visco-elastic surfactant (VES) drilling mud is a WBM which can restore the rheological properties.
2. **Oil-based mud (OBM):** OBM uses oil as the base fluid and is comparatively complex in nature and costly. The advantages of OBM include: lower fluid loss control, no shale swelling, drilling bit lubrication, and good transportation of cuttings.
3. **Synthetic-based mud (SBM):** SBM uses synthetic material as the base fluid, which is less toxic and more environmentally friendly. Esters or ethers, etc. are used as synthetic materials and have high kinematic viscosity making pumping difficult. However, now, linear alpha olefins, linear paraffins, and isomerized olefins with lower kinematic viscosity are used to circumvent the issues related to pumping.
4. **Emulsion drilling mud:** This has two phases, i.e., water/brine as the external phase and oil/synthetic hydrocarbons as the internal phase. One surfactant is used to make the two phases miscible. It is environmentally friendly, especially for disposal.
5. **Invert emulsion mud (IEM):** As the name suggests this is the inverse of emulsion mud, i.e., the external phase is made up of oil/synthetic hydrocarbons, whereas the internal phase is made up of water/brine. Here also a surfactant is used to obtain better fluid stability.
6. **Air drilling fluids:** Air drilling fluids are generally used in underbalanced drilling and where there is no contact with reservoir hydrocarbons or water. The advantages of the air drilling process include high rate of penetration, no solid contamination, no formation damage, and no lost circulation [23].
7. **Foam fluid:** This is another kind of mud fluid normally used in ultradeep water drilling with a narrow pressure window. Inert gas is used as surfactant. This has better control over equivalent circulating density.

4.3.2 PURPOSE OF DRILLING FLUID AND TYPES OF DRILLING

In this section, a basic idea about the use of drilling mud/fluid and types of drilling process are outlined. Process description and equipment details are beyond the scope of this book for which standard books on drilling may be referenced. The major purposes of drilling include the following:

- Cooling and lubrication of drill bit;
- Removal of cuttings out of the well;

- Maintenance of annular fluid column for balancing;
- Primary well control barrier.

There are numerous complexities around problems associated with measurements of drilling fluid parameters (mainly associated with flow and density). Each hole has a new set of parameters. Depending on the composition and pumping rates, mud can show various types of flow behavior. The situation is further worsened due to an interface with other fluid interfaces, such as cement, mineral, dissolved acids, etc. There will be variable flow rate, transient flow conditions, and variable densities, and there will also be requirements for quick kick detection (subsea). On account of all these issues, it is quite difficult to select the most appropriate meter type and meter range. Also, some meters are not suitable for various fluids, e.g., EMFM is suitable for WBM only. Based on drilling types, the types of meter and flow-measuring points may vary. *What are the drilling types?* There are two types of drilling, flow measurement requirements for conventional drilling and managed pressure drilling (MPD) are different.

Why go for MPD? In conventional drilling the bottom hole pressure (BHP − Ref: Fig. VII/4.3.0-1) is determined by the effective circulating density (ECD − Ref: Fig. VII/4.3.0-1), i.e., mud weight + frictional pressure loss. Therefore, pump control is the means of control. In contrast, in managed pressure drilling, BHP is determined by ECD and applied surface back pressure. *Therefore, there is an additional parameter, back pressure, which can be lowered upon detection of mud loss and can be increased on detecting kick. The kick detection phenomenon* ***improves safety***.

In the case of earlier conventional drilling use of paddle wheel meters was common to indicate the percentage flow return, whereas in the case of modern MPD Coriolis flow meters are deployed before a mud gas separator for better accuracy and pressure control. Also SONAR type flow meters are applied for high-pressure injection as there is no Coriolis solution for high-pressure injection. SONAR type meters have limited use in return line as their accuracy degrades with reduced turbulence [24]. As stated earlier, EMFM is suitable for WBM only, also it is not suitable for high-pressure stand pipe application.

4.3.3 CORIOLIS METERS IN DRILLING OPERATIONS

In order to reduce nonproductive time and improve the efficiency/safety of drilling operations, it is necessary that there shall be continuous, accurate, and reliable measurement of the drilling fluid flow rate and density. Since in Coriolis meters both functions are well achieved, Coriolis meters find their uses in drilling operations.

1. **Use of Coriolis meters in flow measurement:** In the following list only flow rate measurement cases have been listed (along with density applications of the same fluid). Other than this there are many cases where Coriolis meters are used for *density measurement (beyond the scope of the book—interested readers may consult Reference[25] for further reading)*. The major features and areas of use (flow) of Coriolis meters include but are not limited to the following:
   - Accurate reliable detection of mass/volume flow rate (and density) of mud;
   - Non-nucleonic measurement and hence no chance of exposure to people;
   - Assistance for controlling mud design properties;
   - Capable of quick kick detection;
   - Mud flow rate in mixing systems (and mud density);
   - Kick detection and loss of circulation also in MPD for enhanced measurement;
   - Returns mud flow (and density) for well control.
2. **Meter challenges:** The following meter challenges are common in use of Coriolis for drilling operations.
   - *Different fluid bases and properties of fluids:* For a Coriolis meter it is direct mass (intrinsic property) flow and so independent

of fluid base and type. Also, measurement is unaffected due to the changes in temperature, density, viscosity, composition, etc. This means an appropriately sized sensor can be used to measure water, oil, or synthetic base fluids containing a variety of mud weighting and chemical additives used in drilling fluid [25].

- *Harsh environments and process conditions:* Coriolis meters are capable of handling fluid where there could be sudden changes in flow surges, slug large particles such as cuttings. Coriolis meters can handle high temperatures and pressures normally encountered in drilling applications (pressure up to 200 bar).
- *Variable flowing rate:* The drilling operation at times behaves like on off operation, involving a sudden reduction in fluid circulation rate, etc. MPD involves a high turndown ratio, which Coriolis is capable of catering to.
- *Entrained gas:* A Coriolis sensor will measure the mass rate and density of a two-phase fluid. At low gas volume fractions $\leq 5\%$ it measures the mass flow [25].

Now we look into the paddle wheel flow instrument used frequently in drilling operation.

4.3.4 PADDLE WHEEL METERS IN DRILLING OPERATIONS

Especially in conventional drilling, paddle wheel flow sensors are used with pump stroke counts for flow tracking/monitoring necessary for drilling fluid hydraulic calculations and well controls. Paddle wheel sensors (Ref: Chapter V) are also sometimes referred to as vane type sensors. These are used in inflow and outflow pipes and for monitoring return flow percent indications. A typical paddle switch is shown in Fig. VII/4.3.4-1.

1. **Features:** This is an inline flow meter used for flow measurement of drilling mud, slurry, cement, and completion fluids at the in- and outflow of the trip tank.
   - Low power integrated gap sensor with integrated display.

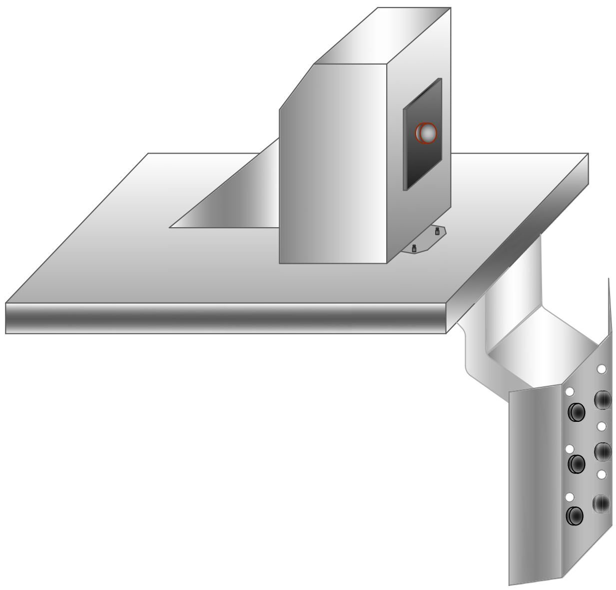


FIGURE VII/4.3.4-1 Paddle wheel flow instrument.

   - Meters are available for hazardous location mounting.
   - Available in rugged SS316 construction for harsh process conditions
2. **Specification:** The following are major technical data of the instruments:
   - *Sensing:* 0–90 degrees vane rotation;
   - *Length:* Normally with 900 mm with possible extension;
   - *Materials:* 316 SS with SS housing and enclosure;
   - *Process connection:* universal flange;
   - *Power supply:* 24 VDC (14–30 VDC);
   - Output 4–20 mADC, HART protocol;
   - *Enclosure class:* IP66;
   - *Hazardous application:* Possible.

Apart from these types of flow meters, magnetic flow meters and also ultrasonic flow meters have been seen in drilling fluid flow measurements. With this, the discussions on drilling fluid flow come to an end and we now investigate slurry flow in pulp and paper industries.

4.4.0 Pulp and Paper Slurry Flow Measurement

Flow measurement in paper plants is really a challenging one. In fluid flow measurements there

are challenges from corrosive chemicals, high temperatures and pressures, and abrasive slurries. Therefore, the selection of flow meter type and suitable materials of construction of the meters is not an easy task. There are two types of flow meters mainly found in paper plants, these are magnetic flow meters and ultrasonic flow meters. Coriolis flow meters are also used. Since this section is meant for slurry and complex flow measurement our major concentration will be on the same. Discussions on flow meter applications in various plants have been presented in Chapter XII. We quickly review the basic process here so as to understand the challenges therein.

4.4.1 PULP PROCESS OUTLINE

For the production of paper, as well as sanitary products like nappies or tissue paper, pulp is necessary. Pulp is major material for the production of paper as well for the production of sanitary products. Primarily wood chips are used as the basic raw material to obtain the cellulose fibers contained in wood. The following are the basic steps necessary to get the pulp output:

1. **Cutting:** Wood is cut into wood chips;
2. **Cooking:** The wood chips are placed into a digester for boiling cellulose, i.e., to digest the wood chips under considerable pressure and at temperatures of around 300°F in a caustic solution termed white liquor, mainly composed of sodium hydroxide and sodium sulfide. This mixture of wood chips and liquor is heated by steam to dissolve wood chips;
3. **Removal:** At the digester the binding agent lignin is released and removed;
4. **Output:** The output is pulp which, after the cooking, is discharged from the bottom of the digester through a blow valve and into the blow tank;
5. **Important materials:** Water is another important raw material in this process, so measurement of the same is also pertinent and important.

4.4.2 MEASUREMENT CHALLENGES

Measurements of black liquor in the circulation/extraction process and pulp slurry in the blow line are not only very difficult but also a challenging issue on account of the following:

1. High level of slurry noise generation and non-stability of output;
2. Deterioration of electrode seals and tube liner abrasion resulting in a shorter life expectancy of the flow tube [26];
3. The very corrosive nature damages the liners;
4. Adhesive nature of black liquor creates a coating at the electrodes;
5. Due to the highly aggressive black liquor, there is a requirement for regular maintenance and frequent cleaning.

4.4.3 ULTRASONIC FLOW METERS IN PAPER PLANTS

Since ultrasonic flow measurements are noninvasive and nonintrusive, instrument sensors and detectors do not come into contact with the aggressive medium flowing inside the pipe. As a result of this there will be no wear and tear and practically maintenance-free measurement can be carried out and there should also be a long service life. Installation and start-up will be easier, and instrument replacement is very easy. In both cases there would not be any process interruption. Paper plants require a lot of water so, without a change in the inventory, the same ultrasonic flow meters can be utilized. Normally accuracy of around 1% AR will be available from US meters.

4.4.4 EMFMS IN PAPER PLANTS

During the discussions on EMFMs it has been stated that EMFMs can be used for almost all process applications and paper plants are no exception. EMFMs find their applications in the measurement of aggressive, slurry and complex fluids. This discussion starts with the features of EMFMs that have made them suitable for slurry and complex flow measurements in this application area.

1. **Features:** The following features of EMFMs make them well suited for the applications:
   - Excellent performance, e.g., accuracy and repeatability;
   - Nonintrusive in nature;
   - No impulse line connection and hence no blockages;
   - Possibilities of wider selection of materials for electrodes and liners;
   - Appropriate design of liner to avoid liner failure;
   - Full diameter, no pressure loss;
   - Noise mitigation methods for stock black liquor and lime slurry flows using dual-frequency excitation;
   - High-temperature liquor flows and permeation [27].
2. **Slurry noise:** The major issue of slurry noise is well addressed by a dual-frequency excitation system as discussed in Subsection 3.1.4.4 of this chapter and is definitely a good solution and could be considered for measurements of difficult fluids like black liquor. For high slurry noise reduction enhanced high-frequency excitation can be considered. Many suppliers offer high-end signal processing, including digital signal processing (DSP), and high DC pulses. Some suppliers like Rosemount use selective frequency for excitation based on other physical parameters. In this connection, Table VII/4.4.4-1 may be referenced.
3. **Liner:** As discussed earlier in this chapter, injected molded PFA is a good solution as a liner material in slurry flow. A ceramic liner is also slurry-resistant. In the place of ordinary PTFE, sintered PTFE can also be used.
4. **Diagnostic:** Advanced diagnostic features in modern EMFM are well utilized for early prediction of electrode coating and assessing the signal-to-noise ratio and slurry noises, e.g., Scan Master of ABB electromagnetic flow meter.

SONAR, discussed earlier, is also applied in paper plants to address the challenges of flow measurements. We now examine the same in the following section.

4.4.5 SONAR IN PAPER PLANTS

For stable continuous production, in a paper plant it is essential to measure flow in the most difficult lines, like the blow line and knotter line. This is a noninvasive way of measurement already discussed, as there will not be any drift due to deposits/damage due to debris and/or variations in conductivity in the blow line (which is not something unusual) like can happen in EMFM, even after lots of necessary steps as discussed above. Also, as it is fitted from the outside there is no need for wasting time due to process shutdown. Therefore, SONAR, already discussed in Section 3.3.0, can be utilized in paper plants also.

TABLE VII/4.4.4-1 Excitation Frequency for Process Noise

Parameters	5 Hz	37.5 Hz	37.5 Hz + DSP
Consistency	0%–6%	4%–10%	6%–10%+
Chemical addition	Add 1% point for chemical addition		
Fiber length	Short fiber	Medium fiber	Long fiber
	Subtract 1%	No change	Add 1%
Velocity normal	<3 ft/s subtract 1%	3–10 ft/s no change	>10 ft/s add 1%
Viscosity	Low no change		High add 1%
Solid content	Low solids content no change		High solids content add 1%

Adapted from Pulp and Paper Process Solutions Guide: Pulp and Paper Flow Meter Guide, Micro Motion, Emerson Process Management. http://www2.emersonprocess.com/siteadmincenter/PM%20Micro%20Motion%20Documents/Pulp-Paper-PSG-Flowmeter.pdf.

With this, the discussions on paper plant slurry flow come to an end, and we now focus on metallurgical plants, like RED mud in an alumina plant.

4.5.0 Metallurgical Slurry Flow Measurement—Alumina Plant and Red Mud

Slurry flows are very important for the metallurgical process of material transport in metallurgical and minerals processing. Red mud in alumina plants is one of the most important materials that need handling in the metallurgical process. Accurate measurement of slurry, especially in alumina plants, is a real challenge for process control engineers because of its abrasiveness and tendency to agglomerate.

4.5.1 ALUMINA PLANT AND RED MUD

Basically, alumina plants can be divided into the following stages:

- Bauxite grinding;
- Predesilication;
- Digestion and dilution;
- Settler washer;
- Security filtration;
- Precipitation and classification;
- Calcination;
- Evaporation and utility.

Of these stages, the last stage mainly comprises of a utility boiler, turbine, etc. and major flow measurements are water steam. Other stages there are slurries and abrasive chemicals. Details of these stages and typical flow meters are listed in Table VII/4.5.1-1. From this table it is clear that red mud in alumina plants is an important issue of slurry flow measurement.

1. **Red mud production:** This is important not only because it is a difficult material to handle, but also for the quantity produced. Based on the raw material used, 1−2.5 tons of red mud are generated per ton of alumina produced. Red mud is a reddish brown-colored solid waste/byproduct produced during the physical and chemical processing of extraction of alumina from bauxite.
2. **Red mud properties:** We know that bauxite is composed of aluminum hydroxide minerals, including primarily gibbsite ($Al(OH)_3$), boehmite (γ-AlO(OH)), diaspore (α-AlO(OH)), hematite (Fe_2O_3), and goethite (FeO(OH)) [28]. There are three kinds of red mud: Bayer's process red mud, sintering red mud, and combined process red mud. Red mud is a mixture of

TABLE VII/4.5.1-1 Flow Measurements in Different Stages of Alumina Plant

Stage	Product Measurement	Flow Meter
Bauxite grinding	Mother liquor, abrasive bauxite slurry, and red mud	EMFM
Predesilication	Red mud (a measure of ore quality)	EMFM
Digestion and dilution	Caustic soda, slurry (abrasive, high temperature and pressure)	EMFM
Settler washer	Flocculent dosing chemical dosing	EMFM
Security filtration	Slurry and liquor	EMFM
Precipitation and classification	Hydrate slurry, seed slurry, and water flow	EMFM
Calcination	Hydrate slurry	EMFM
Evaporation and utility	Steam and other flow	Vortex, DP

various materials originally present in the ore and of compounds formed or introduced during the process. It is disposed as slurry having a solid concentration in the range of 10%–30%, pH in the range of 10–13, and high ionic strength. There has been a lot of work to determine the best use of the same in terms of its storage, disposal, and utilization. In any case, in each of these steps it is necessary to transport the slurry and measure the flow rate of such transportation. Here our main objective is to see how to measure that difficult slurry, i.e., how to handle it. The use of an electromagnetic flow meter, vortex (in utility section), Coriolis meter, and DP elements (wedge in slurry and orifice, flow nozzle in utility section) is not uncommon. In these discussions both EMFMs and wedge elements will be covered.

4.5.2 ELECTROMAGNETIC FLOW METER IN ALUMINA PLANT—RED MUD

As stated earlier many times, electromagnetic flow meters are practically universal flow-metering devices that can cater to almost all fluid flow measurements. This is also clear from Table VII/4.5.1-1. There are a number of issues to be addressed for measurement of these slurries, especially for red mud flow measurements.

1. **Major challenges:** The major challenging issues are listed here:
   - *Slurry noise:* High slurry noise affects measurement accuracy and stability;
   - *Liner abrasion:* The abrasive nature of aluminum slurry damages electrodes and the liner and this causes flow measurement fluctuations and highly affects the measurements;
   - *Adhesive:* The adhesive nature of slurry causes an electrode coating to introduce measurement fluctuations;
   - High maintenance requirement and shorter replacement time.
2. **Typical solutions:** Some solutions to the above challenges have been discovered by major manufacturers. Some of these have already been covered previously, but are discussed again in brief and other issues are discussed in detail.
   - *Excitation system:* The removal of slurry has already been discussed; this can be based on dual-frequency excitation and/or selective frequency excitations, as already discussed in Section 3.1.4. Therefore, the same is not repeated here.
   - *Sensing type:* Caustic base liquor in red mud application quickly forms a thin hard insulating layer on pipe walls. This coating is extremely difficult to remove. For red mud applications a capacitance electrode could give better measurement stability and will not be affected by the adhesiveness of the mud, e.g., ADMAG CA of Yokogawa. The manufacturer claims the replacement requirement for an electrodeless meter will be extended to 12–18 months, in comparison to the requirement of the same for a conventional one being 2–3 months. Also, these can work with coating and flow can be calculated in DCS.

4.5.3 WEDGE FLOW ELEMENT IN ALUMINA PLANT—RED MUD

Flow measurement with a wedge flow element is an economic solution for slurry measurement. Flow of aluminum oxide slurry can be measured with suitable temperature compensation. However, when the slurry is not so corrosive, with the presence of water and the abrasive nature of the solids it is normally made up of 316L stainless steel as the material of construction for the primary flow element. Flow measurement with good accuracy and performance characteristics (discharge coefficient) are possible even for low Reynolds' number in this meter. Therefore, it is possible to get accurate measurement of process flow with compensation for pressure and temperature variation. As shown in Fig. VII/5.0.0-1B, remote seal connection for DPT or MVT is possible. Many MVTs have provisions for diagnostic features for temperature element failure. Modern intelligent transmitters have HART and

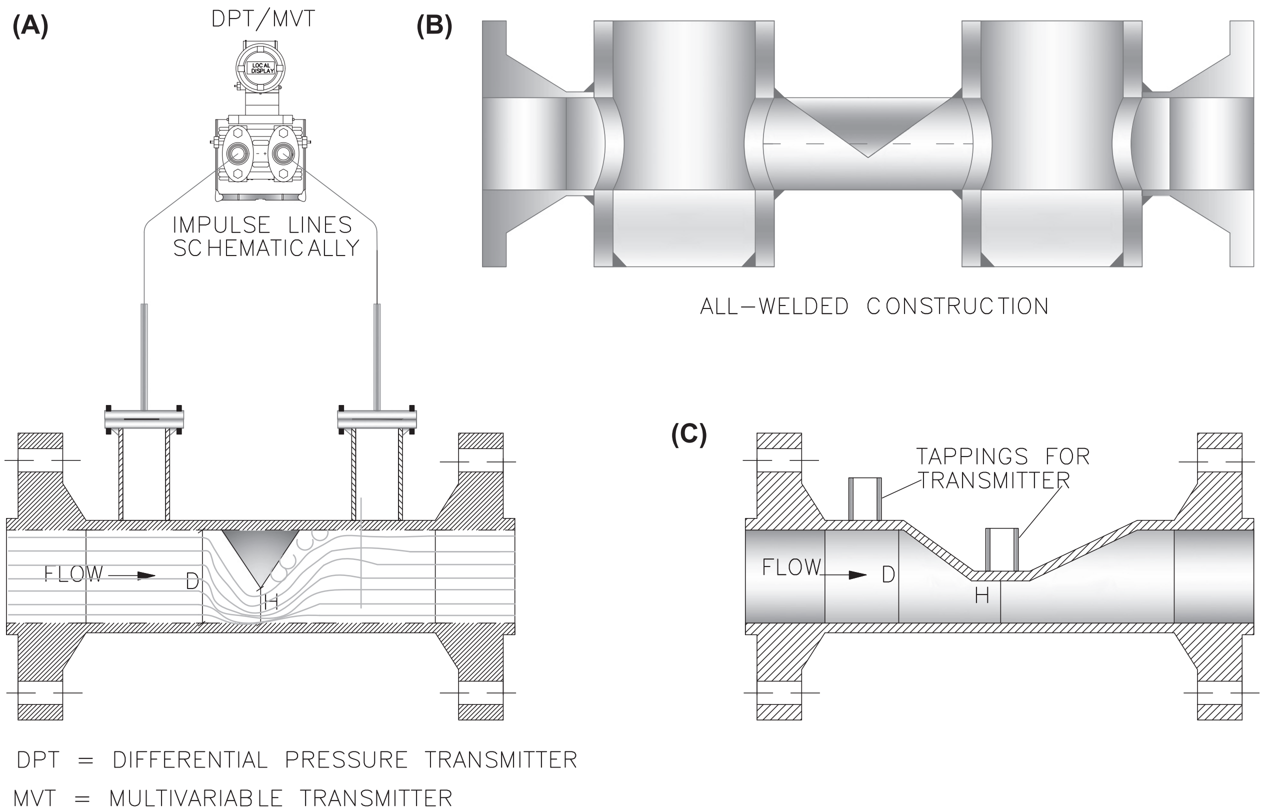


FIGURE VII/5.0.0-1 Wedge element details. (A) Normal wedge with transmitter. (B) Wedge for remote seal transmitter. (C) Eccentric wedge.

fieldbus communication facilities also. With a wedge element there is no moving part, hence it is less prone to maintenance and measurement is unaffected by entrained solids. Flow measurement accuracy of <0.5% is possible with wedge elements, which have been discussed at length in Section 5.0.0.

Like slurry flow, flow measurements in complex fluid at times are also problematic. In the following section short discussions are given on food and beverages.

4.6.0 Complex Fluids in Food and Beverages

In the food and beverages industries efforts are always made to maintain consistency of taste, texture, appearance, etc., in products. Otherwise, in the case of taste variation there will be every possibility that customers may switch to other brand. Therefore, density and concentration, etc. are very important. Naturally, for these cases it is quite common to use Coriolis meters for the main ingredients and for final product flow, density, and concentration measurement with greater accuracy. On the other hand, water used to dilute, e.g., any concentration may be measured by EMFM. However, in these industries there are many complex flow measurement requirements, such as flow rate in mayonnaise or chocolates. In such applications PD meters are frequently used.

With this the discussions on slurry and complex fluid flow measurement come to an end. Now discussions will be presented on wedge flow meters.

5.0.0 WEDGE FLOW ELEMENT

This is a kind of differential pressure-producing element used to measure flow rate. This type of flow element can also be used for measurements of liquid, gas and steam. Wedge elements are very commonly used for slurry flow measurement.

5.1.0 Theory of Operation

Basically, a wedge element can be thought of as a special segmental orifice with special design. However, there are a number of differences between the two. In this section discussions shall be presented on the basic principles of operation and mathematical formulations of the flow element along with formulas for volume flow.

5.1.1 OPERATIONAL PRINCIPLES

Like other differential producing elements like orifices and flow nozzles, the functional principle of a wedge element is based on the Bernoulli principle (continuity and energy balance equations). In fact, a wedge meter is a refinement of a segmental orifice. With the help of an engineered slanting edge the pipe fluid is forced downward, similar to a segmental orifice plate. The only difference is that here, in place of the sharp edge of the segmental orifice, there is a sloping/slanting edge in the wedge element. As shown in Fig. VII/5.0.0-1A, with the help of a V-shaped flow restrictor (normal wedge element, however, there are eccentric type wedge elements also discussed later), the area available to flow is reduced in the wedge element.

On account of this reduced area, fluid velocity increases, when the fluid flow is contracted at the flow restrictor. The increase in velocity means there will be an increase in the kinetic energy of the measuring medium. By the principle of conservation of energy, any increase in one form (here kinetic energy) must be compensated for by a corresponding decrease in energy of another form, i.e., potential energy (static pressure). Therefore, the fluid pressure upstream of the flow restriction has a higher static pressure (greater potential energy) and will lose potential energy (i.e., pressure) to gain kinetic energy. Therefore, a differential pressure will be created between the upstream and downstream of the restriction, similar to a segmental orifice. Therefore, by applying Bernoulli's energy equation, the generated differential pressure can be equated with the volume flow (or even mass flow). Pressure taping on either side of the wedge element can be utilized to measure the differential developed due to the imbalance in potential energy. The volume flow rate can then be directly calculated from the measured differential pressure. Like the majority of differential-producing elements discussed earlier in this book, part of the pressure loss created by the flow restriction will be recovered downstream of the wedge element as kinetic energy is converted back to potential energy when the fluid comes out of restriction. *How could it be used in slurry flow applications?*

As stated earlier, the segmental orifice has a sharp edge and wedge elements offer gradual slanting. This makes it offer much more immunity to erosion and to build-up by secondary phase. Thus, there is less possibility of damage due to impingement with any entrained solids in the measuring medium. In slurry applications where there are entrained abrasive solids, e.g., red mud application, it could be chosen as a flow element. The opening beneath the restriction is large and allows for easy passage of any secondary phase. Eddies and backcurrents created provide a "*self scouring*" action that keeps the internals clean and free from build-up [29].

5.1.2 MATHEMATICAL FORMULATION FOR WEDGE FLOW ELEMENTS

The discharge coefficient of the segmental wedge is different from that at the segmental orifice. The theoretical volumetric flow rate can be obtained as detailed below by applying the continuity and Bernoulli equations (in this connection Chapter I discussions may be recalled):

$$q_{\text{theoretical}} = \frac{\varepsilon Y A_c}{\sqrt{(1-m^2)}} \cdot \sqrt{\frac{2\Delta P}{\rho}} \quad \text{(VII/5.1.2-1)}$$

where ε = the expansion factor for compressible fluids; Y = the thermal expansion factor; m = equivalent beta ratio, i.e., ratio of restricted area to pipe area; ΔP is the differential pressure; and ρ = fluid density. With reference to Fig. I/3.1.1-8 one can see that ΔP is a function of

H/D. Now we shall try to relate these. However, prior to that we define another term, **Z**.

Z = H/D; where H represents the height of the opening below the restriction and D is the internal diameter of the pipe. So, H/D ratio is analogous to the beta ratio of a concentric orifice plate. Thus Z = H/D is often called the equivalent beta ratio. The area restriction in a wedge meter is characterized by the H/D ratio. The H/D ratio can be varied to create a desired differential pressure for any specific flow rate. This gives the user a good degree of flexibility in selecting a suited wedge meter for a given application [29]. Now we see how m is related to the H/D ratio. From the literature it has been found that nondimensional equivalent beta ratio m can be expressed as [30,31]:

$$m = \frac{1}{\pi}\cdot\left\{\cos^{-1}(1-2Z) - 2(1-2Z)\sqrt{Z(1-Z)}\right\} \quad \text{(VII/5.1.2-2)}$$

As indicated in Chapter I discharge coefficient C_d, is an important factor to relate actual flow with theoretical flow, hence $C_d = \frac{q_{acual}}{q_{theoretical}}$.

Thus we see from Eq. (VII/5.1.2-2), Z(=H/D) is related to ΔP in VII/5.1.2-1 through m.

$$\text{Also, } q_{actual} = C_d\cdot\frac{\varepsilon Y A_c}{\sqrt{(1-m^2)}}\cdot\sqrt{\frac{2\Delta P}{\rho}} \quad \text{(VII/5.1.2-3)}$$

Here the equation contains A_c and m which are dependent on the particular element so they should be eliminated. After replacing $A_c = \frac{\pi m D^2}{4}$ and eliminating m one gets

$$\text{Liquid volume flow: } q = N\cdot Y\cdot (C_d)^2\cdot\sqrt{\frac{\Delta P}{g_f}} \quad \text{(VII/5.1.2-4)}$$

where N is the numerical dimensional constant; and g_f is specific gravity.

Here only the liquid flow equation has been shown, similarly equations for gas can be found by applying adiabatic expansion compressibility factors.

5.1.3 DISCHARGE COEFFICIENT

In this section short discussions are presented on the important issue of discharge coefficient with the effect of tapping point location and the shape of the wedge. From the above we get the discharge coefficient C_d for the wedge element. In the case of the wedge element, C_d is meant to cover a wide range of flow regimes, almost the entire flow regime. From large turbulent flow then down up to a Reynolds number nearly (<) 500 C_d is almost horizontal and linear as is shown in Fig. VII/5.0.0-2A meaning that it can offer good performance characteristics even in the lower side of Reynolds number, i.e., wedge elements are designed to measure all flows: laminar, transition, and turbulent. Laminar and transition flow regimes are often encountered with viscous or low flow rates and in such cases there may be significant deviation from the square root relationship between flow rate and measured differential pressure. There can be variations in the shape of the wedge.

Of these, the most commonly used are 90 degree wedge angle and 60 degree wedge angle. The edges can be sharp or rounded.

There are various wedge designs differing in wedge angle as well as wedge tips. For both wedge angle designs, for a given pressure taps discharge coefficients are constants. However, absolute values in 90 degree wedges will be relatively higher than for 60 degree wedges [32]. This is because, in the case of 90 degrees, more guidance is available for fluid flow. For the 60 degree rounded off design, losses are drastically reduced due to reduced wake size and shift of the vena contracta [32]. A similar effect is noted for 90 degrees but with lesser effect. From this it should be noted that the rounded off design will give rise to less pressure loss and is better suited for liquids with solids because it will have less wear. Tapping point locations at D distance upstream from wedge tip and downstream could be represented as D-D tapping. It has been found that D-D and 2D-D sets of tapping points do not have a significant effect on C_d. However, for

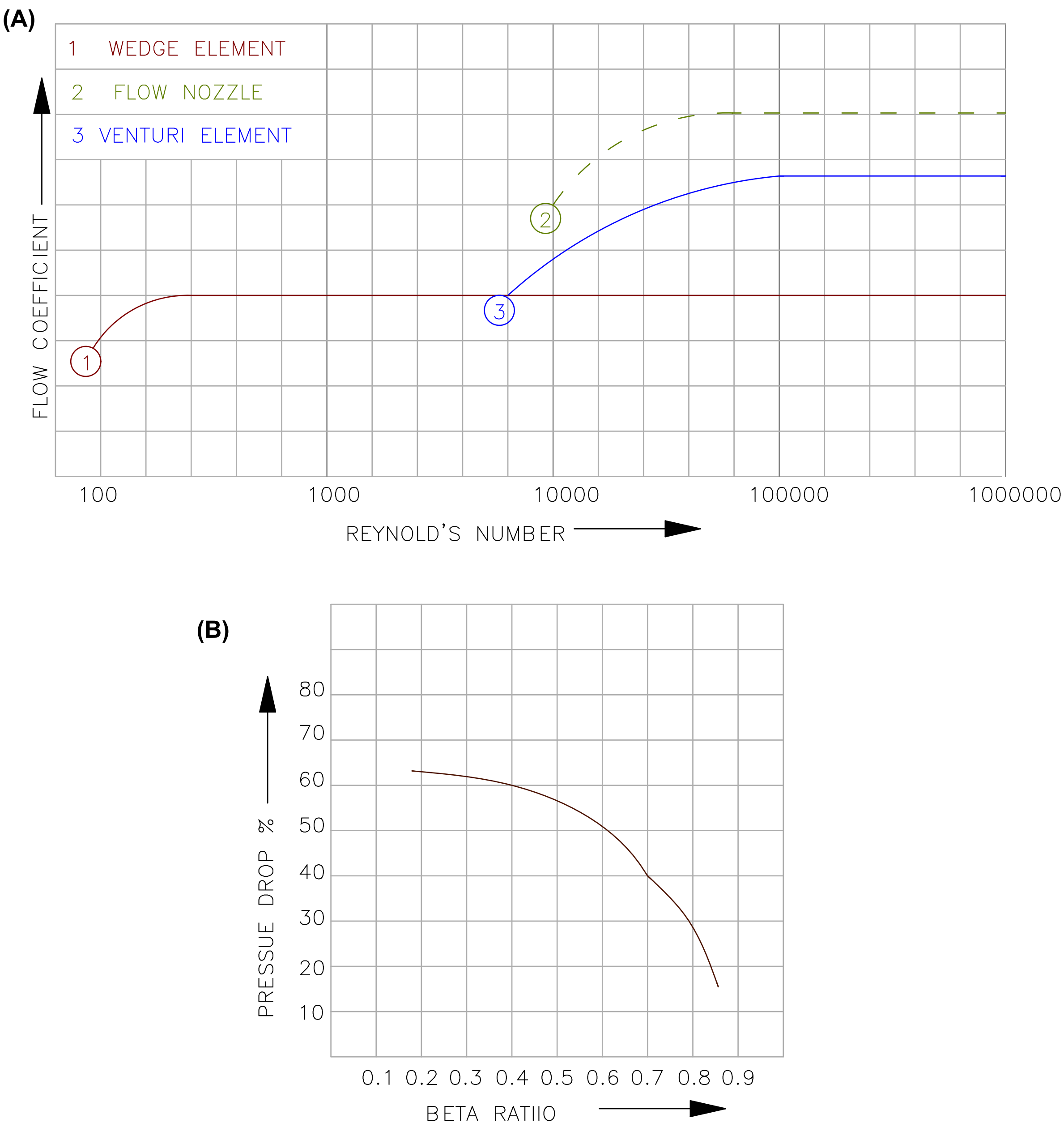


FIGURE VII/5.0.0-2 Wedge element performance curves. (A) Comparison of flow coefficients of DP elements. (B) Pressure (%) of wedge element.

2D-2D tapping, the value of discharge coefficient changes sharply [32]. This is because at that long-distance downstream tapping point, there may or may not be a zone of separation downstream of wedge element. Taping style D-D may be the optimum tapping point location.

5.1.4 WEDGE (H/D) RATIO

The H/D ratio for wedge elements may vary from 0.2 to 0.7. It is worth noting that there are normally four H/D ratios for which manufacturers develop their wedge elements and each of these

has different discharge coefficients, C_d. However, in some cases there may be more than four H/D ratios available for a wedge element (e.g. ABB FPD470 which has five H/D ratios for higher size elements; refer to Table VII/5.2.3-1). The H/D ratio is an important factor for wedge elements. Discharge coefficient, flow capacity, and accuracy and DP for measurement of even straight length requirements for a wedge element are all specified in terms of wedge ratio (H/D) for wedge elements, and this will be clear from the subsequent discussions and the various tables below. We now concentrate on the description of the meter.

5.2.0 Descriptive Details of Wedge Elements

In this section a short description of the elements, operating conditions, performance, and materials of constructions are covered.

5.2.1 DESCRIPTION OF WEDGE ELEMENTS

Wedge flow elements are mostly applied in difficult-to-meter line fluids, like air-entrained liquids, solid particle-entrained liquids, highly viscous liquids, or slurry liquids. In the majority of cases these are abrasive or fibrous, e.g., red mud slurry, pulp slurry. As the wedge element is asymmetric about the pipe cross-section and is free at the bottom of the pipe, it is used for a variety of corrosive, erosive, and highly viscous fluids and slurries. However, this does not mean that these are not applied for other fluids. They are also applied for clean liquids, gas, and steam. However, on account of the higher pressure drop in clean fluids these elements are less preferred flow elements.

1. **Constructional details:** With respect to construction, there is some difference between small wedge elements and larger pipes. Normally for sizes $\leq$50 mm the wedge is developed by cutting a V notch in the pipe, while in larger sizes V notches are fabricated from steel plates properly welded together and then inserted into the pipe, so these are basically fabricated ones for large pipes. As mentioned earlier, these slant edges can be at any angle, but 60 and 90 degrees are common. Wedge tips may be rounded or sharp edges. The slanting upstream face of the wedge element develops a sweeping action to give a scouring effect. This action helps in cleaning and disallowing build up, and also ensuring that the face is not subject to wear due to abrasive materials.
2. **Tapping points and bidirectional flow:** Usually the pressure taps are kept equidistant from the wedge tip but optimum results may be obtained for 2D-D distances for tapping points (with upstream and downstream sides measured) from the wedge tip. However, D-D could also be used. For corrosive, highly viscous and dirty fluids it is recommended that a remote seal transmitter should be used. This is shown in Fig. VII/5.0.0-1B. A typical segmental wedge meter is provided as a complete assembly combining the wedge element and the pressure taps into a one-piece unit [33]. Because of the symmetric design of wedges in the upstream and downstream sides, i.e., because of the isosceles triangle profile of the wedge element it can be used for bidirectional flow measurement with symmetrical pressure tapping point locations about the wedge tip.
3. **Measurement:** By determining the difference in pressure between the two tapping points, the volume flow of the fluid can be calculated and also the mass flow can be computed, as already covered in Section 5.1.2, with all other characteristics of the measuring points constant. Normally there are four/five different selectable H/D ratios to cover a multitude of flow rates.

5.2.2 OPERATING CONDITIONS AND FLOW CAPACITY

In this section brief technical data on the operating conditions of wedge elements and size with flow capacity are discussed. The data are taken from various reputed manufacturers and extreme data shall be presented. Therefore they may not match any particular manufacturer but would be helpful for the designer in assessing maximum possible conditions.

1. **Operating conditions:** The following are the major operating condition data:
   - *Pressure:* Lower side 10 bar and upper side 100 bar. With a remote seal it could be 200 bar;
   - *Temperature:* −40°C to 400°C, in some cases it could be up to 800°C;
   - *H/D:* Available in 4−5 ranges between 0.2 and 0.7; normally four: 0.2/0.3/0.4/0.5;
   - *Pipe connection:* Flange normally, as per ANSI B16.5;
   - *Instrument tapping:* Flange normally, as per ANSI B16.5.
2. **Meter size and flow capacity:** Meters are available in various sizes and flow capacity obviously is a function of the H/D chosen.
   - *Sizes:* 0.5−24 inches (15−600 mmNB);
   - *H/D:* 0.2/0.3/0.4/0.5.

One important point to note is that the wedge capacity is a function of three parameters, namely line size, H/D ratio, and chosen differential pressure span. Many manufacturers specify the DP range for the element, such as 160, 650 mbar, etc. For optimum accuracy it is better to select the full-scale DP as close as possible to the maximum range for the sensor [34].

Table VII/5.2.2-1 shows the typical flow capacity of wedge elements for some selected line sizes. It is worth noting that for the same line size and H/D ratio the flow capacity also varies with the DP ranges selected. The data given here are based on a DP of nearly 7 bar. In the table flow coefficient variations have also been show, this is for the guidance of the reader. As stated earlier, there will also be variation due to the chosen DP range. For this, necessary software for sizing is available from the manufacturers.

5.2.3 PERFORMANCE DATA

1. **Accuracy:** Generally speaking, the accuracy available with wedge elements is <25 mm for 0.75% AR flow and for >25 to 600 mm it is 0.5% AR flow. These figures represent the accuracy when wet calibration is done. However, if uncalibrated, the accuracy will be 5% (<25 m) and for >25 to 600 mm it is 3% AR. One needs to add the transmitter accuracy to the accuracy from the wedge element to get the total accuracy of the measurement. In most cases the manufacturers specify the accuracy, as shown in Table VII/5.2.3-1
2. **Repeatability:** Generally ±0.2% AR

TABLE VII/5.2.3-1 Accuracy for Wedge Elements

Pipe Size in mm	Wedge H/D Ratio	Accuracy in % Flow Rate (+Tx Accuracy Also)	
		Wet Calibrated	Uncalibrated
15	0.2/0.3/0.4/0.5	±0.75%	+5%
25−40	0.2/0.3/0.4/0.5	±0. 5%	+3 to +5%
50−80	0.2/0.3/0.4/0.5	±0. 5%	+3 to +5%
100−500	0.3/0.4/0.5/0.6/0.7	±0. 5%	+3 to +5%

Courtesy: ABB.

TABLE VII/5.2.2-1 Flow Capacity of Wedge Elements for Water [35]

Pipe Size (Inches)	Flow Capacity (GPM) at 100PSID			Flow Coefficient		
	H/D = 0.3	H/D = 0.4	H/D = 0.5	H/D = 0.3	H/D = 0.4	H/D = 0.5
2.0	45	70	100	0.1896	0.2860	0.4173
6.0	400	600	850	0.1876	0.2882	0.4051
12.0	1520	2250	3140	0.1875	0.2778	0.3889
20.0	3740	5575	7580	0.1862	0.2780	0.3778

Courtesy: MPP wedge meter.

5.2.4 OTHER RELEVANT DATA

In this section short discussions will be presented on materials of construction (MOC) and pressure drops, etc. to complete the discussion.

1. **Materials of construction (MOC):** Standard MOC for wedge elements are CS and 316. Based on the application and use there can be other variations of other materials, including but not limited to:
   - 347H Stainless steel;
   - Hastelloy, Monel, C276 Alloy 25% Cr Super Duplex (UNS S32750);
   - Tungsten carbide;
   - *For sealing gasket:* Silicate-filled TFE;
   - *Chemical tee gasket:* Graphite.
2. **Standards used:** In most cases ASME/ANSI standards are used, the exception being design where the EN standard has been used:
   - Design per ASME B31.3 or EN standard;
   - Welding operations per ASME B31.3;
   - Flanges per ASME B16.5;
   - Fittings per B16.9/16.11;
   - Seamless pipes per ASME B36.10.
3. **Pipe schedule and process flange ratings:** Wedge elements are available for various pipe schedules indicating pressure-withstand capabilities and thickness of the pipe. Pipe schedules starts from 5S/5 through schedule 160 even for XXS. Similarly, these are available for flange process connections with a flange rating in ANSI from ANSI 150 up to 2500 lb and associated equivalent for other standards like DIN and JIS to name but a few.
4. **Pressure drop:** Pressure drop in the case of a wedge obviously varies with H/D ratio and this is a function of the DP range chosen for meter sizing. Typically pressure drop varies between 30% to nearly 65%−67% of the DP range chosen for various H/D ratios, as shown in Fig. VII/5.0.0-2B.

Wedge elements have some features for which they are different from other DP elements and can be used for difficult fluid applications. We now see its features and applications.

5.3.0 Features and Applications of Wedge Elements

Having gained some knowledge about the flow element we now look into the element to see and list the special features of the element and where it finds most of its applications.

5.3.1 SPECIAL FEATURES OF WEDGE ELEMENTS

Various features of the flow element will be clear when we look at the advantages and disadvantages of the element. We now explore these:

1. **Advantages of wedge elements:** The following are the major advantages of wedge meters:
   - Universal measuring element, suitable for difficult fluids also;
   - Proven technology for flow measurements;
   - Symmetrical robust element without any sharp edges, suitable to handle high solid contents and abrasive slurries, as well as highly viscous fluids;
   - It does not have any moving parts;
   - Long life, less/zero maintenance;
   - Steady performance, even up from Reynolds number 500 to large Reynolds number;
   - Good accuracy of 0.5% when wet calibrated;
   - Able to measure bidirectional flow due to symmetry;
   - Wide flow range with variations by changing wedge ratio H/D;
   - Straight length requirements (5D/3D) and pressure loss are moderate;
   - Capable of withstanding various installation styles, even nonstandard;
   - Available in various sizes from 15 to 600 mm, even 1200 mm is also possible (ABB FPD470);
   - Normal impulse connection as well as remote seal and chemical TEE possible.

2. **Disadvantages of wedge elements:** The following are the major disadvantages of wedge meters:
   - There is no specific standard available, such as ISO 5167;
   - When not calibrated accuracy is poor and could be as high as 5% AR;
   - Pressure loss is appreciable from 30% to >60% of chosen DP range. Hence for higher flow capacity losses will be greater;
   - When compared to a V cone greater straight length requirement is necessary.

5.3.2 APPLICATION AREAS OF WEDGE ELEMENTS

As stated during the initial discussions, as well as while describing its features, the wedge element is a universal flow element. It can be used for liquids, air/gas, and steam. However, it finds its usage more in handling difficult fluid slurries. The major areas of use are listed here:

1. Measurement of flow of fluid with high viscosity;
2. Measurement of flow of difficult fluid with high solid content and abrasive slurries;
3. Fluid flow with low Reynolds number;
4. Bidirectional flow measurement;
5. **Major industries covered include:** paper, alumina, tar production, well heads, and waste management of different industries.

5.4.0 Specification Details for Wedge Elements

After gathering some knowledge on technical data on wedge elements, we now look at how this could be specified. Table VII/5.4.0-1 provides a specification for a wedge element. *It is worth noting that the data given here are mainly based on data from reputed manufacturers. Effort has been made to put the best value or material for any specific thing. Naturally, data given may not match with any particular manufacturer. Based on the budget and application, readers should specify their requirements to get the optimum result.*

TABLE VII/5.4.0-1 Specifications of Wedge Elements

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Liquid, gas, steam or two phase—solid-laden liquid/slurries		
2	Design pressure	10–100 bar typical		
3	Design temperature	Normal −40 to 400°C		
4	Flow range	To be specified		Flow capacity, for discussions refer to Subsection 5.2.2.1
5	Other physical parameters	**a.** Upstream absolute pressure, absolute maximum/minimum/normal **b.** Downstream absolute pressure, absolute maximum/minimum/normal **c.** Temperature maximum/minimum/normal **d.** Density **e.** Viscosity @ temperature **f.** Reynolds number: **g.** Gas molar weight **h.** Specific heat ratio **i.** Expansionability factor		**1.** To specify OP = operating maximum pressure/is dictated by flange rating (pipe schedule) and maximum temperature is guided by material selection and application **2.** Data as applicable to be specified

Continued

TABLE VII/5.4.0-1 Specifications of Wedge Elements—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
6	Wedge ratio H/D	Based on pipe size, accuracy, discharge coefficient, and selected DP range to be specified		Based on available H/D to be checked for flow capacity
7	Pipe size schedule	Meter for pipe size between 15 and 600 mm (nominal bore) are standard sizes available. Flow ranges are as per manufacturer's standard based on wedge ratio and DP range to be selected		
8	Tapping style and numbers of pairs	Corner/flange/radius/pipe	To select	To specify quantity
9	Standards	Refer to details in Subsection 5.2.4.2		
	Environmental condition	To specify		
10	Materials of construction	Refer to Subsection 5.2.4.1		
11	Gasket material	Silicate-filled TFE/graphite		
12	Chemical TEE/ remote seal	To specify as required		Based on fluid type
Connection and Mounting Details				
13	Process connection and rating	Flange as per ANSI/BS/DIN/JIS etc. Refer to Subsection 5.2.4.3		
14	Transmitter connection	Normally flange type connections are used		
15	Mounting	Horizontal/vertical/special type of mounting		
Performance and Other General Details				
16	Accuracy	Calibrated accuracy around 0.5% AR flow but uncalibrated accuracy 5%; refer to Subsection 5.2.3.1		
17	Repeatability	0.2% AR		
18	Accessories	Meter support (as applicable), process and instrument connection flanges along with tapping points. If applicable transmitter (DPT/MVT), valve manifold, nuts, bolts		
19	Special feature	If any to specify requirement		

5.5.0 Mounting and Installation Details for Wedge Elements

Basically, a wedge element is a flow element, and hence mounting or fixing the element in the pipeline of the same is more pertinent than installation of an impulse pipe. Installation of PT/DPTs is more important when corresponding transmitters are discussed, viz. Fig. VII/4.2.3-1. The high-pressure connection is always on the upstream side of the *flow direction* arrow and the low-pressure connection on the downstream side.

5.5.1 ELEMENT ORIENTATION AND ALIGNMENT

A wedge element can be mounted in either a horizontal or vertical pipe, i.e., both horizontal and vertical mounting is acceptable. These have been shown in Fig. VII/5.0.0-3.

The important issue here is the alignment of the element with the pipe. For proper measurement the wedge flow element should be installed at a 90 degrees angle to the pipe axis. The wedge element should be properly aligned to avoid additional turbulence, which has little effect however on meter performance.

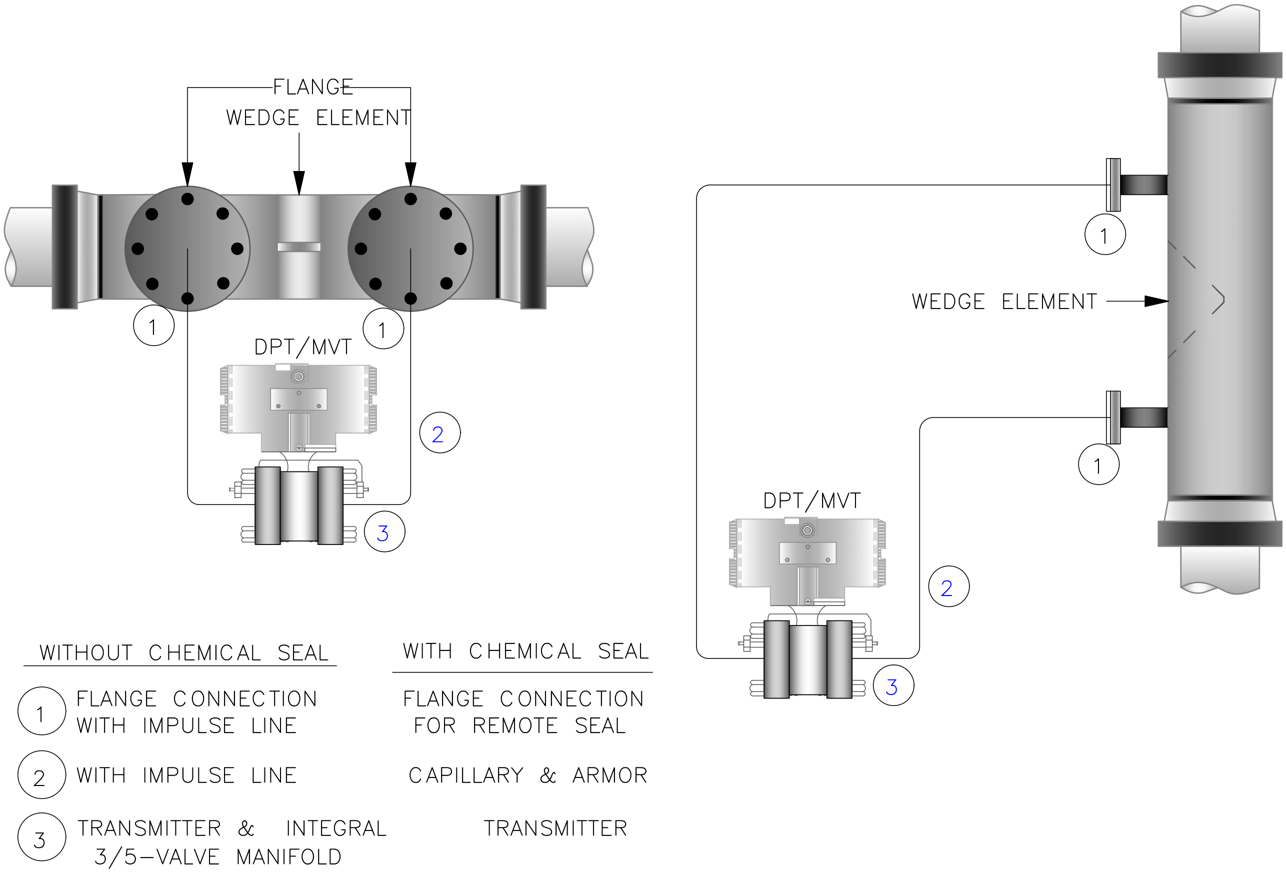


FIGURE VII/5.0.0-3 Mounting and installation of wedge element. *DPT*, differential pressure transmitter; *MVT*, multi variavble transmitter. Note: Bidirectional flow hence *arrow* for flow not shown temperature element for compensation should be in downstream side after downstream pressure sensing point.

5.5.2 INSTRUMENT CONNECTION AND TRANSMITTER TYPES

As stated earlier, the instrument connections are through flanges of suitable rating and standard. There are two variations. One is a transmitter connection with an impulse line and valve manifold and the other is with a remote seal and capillary. Both are shown with suitable notes in Fig. VII/5.0.0-3.

1. **Clean fluid—Impulse line:** In the case of clean fluid, an ordinary impulse line can be laid to connect the transmitter with the element via a three-valve manifold. In the case of DPT/MVT, three- or five-valve manifolds are used.
   - *Three-valve manifold:* In the case of a three-valve manifold, two valves are isolating valves in the two legs of the DPT/MVT and the third valve is the equalizing valve (which should be opened *first* and closed *last* to avoid pressure shock in any of pressure legs for the DPT/MVT for taking the transmitter *into service or taking out of service*);
   - *Five-valve manifold:* In the case of a five-valve manifold, the other two valves are for line drains pertinent to each leg for DPT/MVT.

   For DPT and MVT, integral valve manifolds should be used for better installation and alignment. Based on fluid properties, the materials for the valve manifolds should be selected, normally these are CS and SS. However, it is better to choose an SS manifold so that it can be used for most of the applications.
2. **Dirty/corrosive fluids—Capillary connection:** In the case that the fluid is dirty, with entrained solids, etc. and there is the probability of chocking of the impulse line, or the flow of the fluid to be measured is corrosive and could damage the transmitter, then chemical/mechanical sealing is called for. In the case of a remote seal (e.g., wafer seal), the same is mounted between the two flanges of suitable standard, materials, and rating. A remote seal is connected to the transmitter with the help of a capillary with suitable armor. Naturally there will be no need for a three-/five-valve manifold.
3. **Transmitter type:** As stated at the beginning, the wedge element is basically a DP-producing element, so DP across the element is measured to compute flow as per the details discussed in Section 5.1.2. In order to measure the flow DPT is necessary. In many cases in order to measure mass flow and/or for temperature compensation, MVTs are used. Therefore, the measuring transmitter could be either DPT or MVT. Both DPTs and MVTs are available with remote seals, and can be used for both clean and dirty/corrosive fluids. In the case of MVT and/or when temperature compensation is necessary the tapping for the temperature elements is taken at a point downstream of LP pressure tapping. Normally, the tapping point for the temperature element should be about 6D from the wedge element, where D represents the nominal diameter of the pipe.

There are some requirements of upstream and downstream straight length requirements which are discussed in the following section.

5.5.3 STRAIGHT LENGTH REQUIREMENTS FOR WEDGE ELEMENTS

General straight length requirements for wedge elements are 5D and 3D upstream (UP) and downstream (DWN) respectively. However, these are basically minimum straight length requirements, in reality it is more than this. Also, it is worth noting that the straight length requirements vary with flow capacity, hence with a wedge ratio H/D. Many manufacturers, such as ABB, specify the minimum straight length requirement as well as recommending taking into account the wedge ratio, etc. On the other hand, some specify the same in terms of wedge ratio H/D. In Table VII/5.5.3-1 we specify the straight length requirements for some selected fittings and the straight length requirements for wedge elements at different commonly used wedge ratios. The length requirements are in terms of *multiples of nominal pipe diameters* (D).

TABLE VII/5.5.3-1 Straight Length Requirements for Wedge Elements

	H/D = 0.2		H/D = 0.3		H/D = 0.4		H/D = 0.5	
Fitting Types	**UP**	**DWN**	**UP**	**DWN**	**UP**	**DWN**	**UP**	**DWN**
Single elbow	7	4	9	4	10	4	12	4
Same plane, double elbow	10	4	12	4	14	4	16	4
Two elbows, different planes	20	4	22	4	24	4	30	4
Reducer	9	4	11	4	14	4	16	4
Expander	9	5	11	5	12	5	14	5
Different diameter TEE	7	4	9	4	10	4	12	4
Open shut-off valve	10	4	12	4	14	4	16	4
Open slide valve	7	4	7	4	9	4	10	4
Y run plugged	10	5	10	5	10	5	10	5

5.5.4 MECHANICAL STEPS FOR INSTALLATION OF WEDGE ELEMENTS

The following are a few steps to be followed for mechanical installation described in brief:

1. After unpacking the element it is necessary to inspect to ensure that the supplied element is clean and free from damage and debris.
2. Also, it is necessary to ensure that the flange and gasket rating is suitable for the service and to ensure flow direction for element position and straight length requirements.
3. The next step is to position the meter between the mating flanges and fit sufficient bolts into the lower part of the flanges to retain the meter in place.
4. Correct gasket/sealing rings placement between the flanges on both sides of the meter is important. It is necessary to align the element. Next all the balance bolts are placed and tightened suitably.

With this the discussions on wedge elements come to an end, and along with this the discussions on slurry and complex fluid flow are also concluded. As indicated earlier, it is worth noting that slurry flow is quite common in industries as well as in many other application areas. Slurry flow is an example of two-phase flow measurement. In connection with ***two-phase flow measurement in Section 1.2.0 of Chapter IX***, *further details are available*, so, for complete details, the reader is advised to go to this section.

LIST OF ABBREVIATIONS

ABS Absolute/acrylonitrile butadiene styrene (material)
AC Alternating current
ADC Analog to digital converter
AR Actual reading (in connection with accuracy)
BHCT Bottom hole circulating temperature
BHP British horse power/bottom hole pressure
BHST Bottom hole static temperature
CMRR Common mode rejection ratio
CMV Common mode voltage
CS Carbon steel
DC Direct current
DI Ductile iron
DP Differential pressure
DPT Differential pressure transmitter/transducer
DSP Digital signal processing
EIT Electrical impedance tomography
EMC Electromagnetic compatibility
EMFM Electromagnetic flow meter
ERT Electrical resistance tomography
FC Fail to close (for valve)
FO Fail to open (for valve)
FRP Fiber glass reinforced plastic (thermowetting)
FSD Full-scale division (in connection with accuracy)
GNF Generalized Newtonian fluid
HVAC Heating ventilation and air conditioning
IC Integrated chip/internal combustion (engine)
ID Internal diameter
I/O Input/output
LCD Liquid crystal display
LED Light-emitting diode
LHS Left-hand side
MPD Managed pressure drill
MUX Multiplexer
MVT Multivariable transmitter
NB Nominal bore
OBM Oil-based mud
OD Outer diameter
PD Positive displacement (meter)
PTFE Polytetrafluoroethylene
PVC Polyvinyl chloride
RF Raised face or radio frequency
RHS Right-hand side
RTD Resistance temperature detector
SBM Synthetic-based mud
SIL Safety integrity level
SS Stainless steel
STP Standard temperature and pressure (Fig. I/1.1.2-3)
T/C.TC Thermocouple
US Ultrasonic/United States
VEF Viscoelastic fluid
VM Valve manifold
WBM Water-based mud
WRT With respect to

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CHAPTER VIII

SOLID FLOW MEASUREMENT

Chapter Outline

1.0.0 INTRODUCTION: AN OVERVIEW OF SOLID FLOW MEASUREMENT

The size of solids varies widely, ranging from large size coal flow to a crushing mill, to very fine materials, such as raw meal feed to a cement kiln. In the case of solid flow normally mass flow is measured, as volume flow cannot be considered accurate enough. On account of variations in bulk density, entrapped gas/air mass flow are normally

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measured for measurements of solid flow. The majority of the flow metering depends on some method of weighing. Other meters utilize other phenomena, e.g., centripetal force, impact force, Coriolis, or nucleonic for measuring mass. All weighing systems where the material being weighed is, or may be, in net motion relative to the weighing machine can be referred to as dynamic weighing systems. Therefore, dynamic weighing systems also include indirect weighing methods like Coriolis, impact, and/or centripetal type measurements. These types may also be considered as mechanical types. Apart from these, nucleonic methods and scanners can also be utilized for solid flow measurement. Weighing systems can be utilized in process plants as well as for discrete mass delivery (e.g. Batch control of course a part of process plant), discontinuous totalised system and in motion weighing system. Since the major thrust is on solid flow metering, therefore others systems will be discussed in brief so at first and detailed discussion of weighing systems in connection with solid flow measurement will be discussed at length later. These mechanical type solid flow measurement or dynamic weighing systems can be broadly divided into three categories based on their methods and means of operations as described here [1]:

- **Discrete mass delivery weighing systems:** These are applicable for various weighing machines used in batch weighers or gravity filling machines, where each batch may be put into a container or may be combined with other weighed masses to make up a mixture against a formula.
- **Discontinuous totalizing weighing systems:** These are used for shipping and receiving weighers and in-process weighers. The accumulated total weight of a larger bulk mass of material, and sometimes also the throughput, are recorded.
- **In-motion weighing systems:** In-motion weighing systems are those which determine the mass of a moving material passing over or through a device. The flow of measured mass may be continuous, as in a belt weigher, or it may comprise discrete weighing events, as in the form of road vehicle or rolling stock axles or packages on a conveyor belt [1].

Now short discussions will be presented to give a clear idea about each of these systems.

1.0.1 DISCRETE MASS DELIVERY WEIGHING SYSTEMS

Different discrete mass delivery weighing systems along with their classifications have been depicted in Fig. VIII/1.0.1-1.

Brief discussions on each of these subsystems will now be taken up. The discussions start with a process batch weigher. Chapter XI also deals with dispensing, filling, and batch controls.

1. **Process batch weigher:** There are three types of process weigher systems: cumulative, simultaneous, and combinational batching, as depicted in Fig. VIII/1.0.1-2. Since these are used for batch processing, precise control of the operations is very pertinent and important. Modes of such controls can be manual, semi-automatic, and automatic. In the era of digital

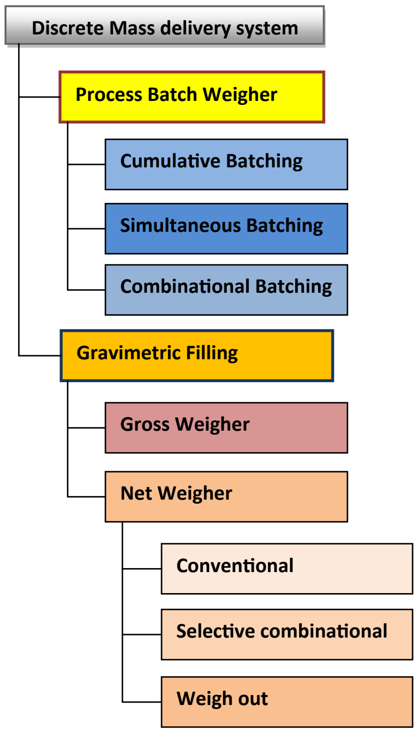


FIGURE VIII/1.0.1-1 Discrete mass delivery system.

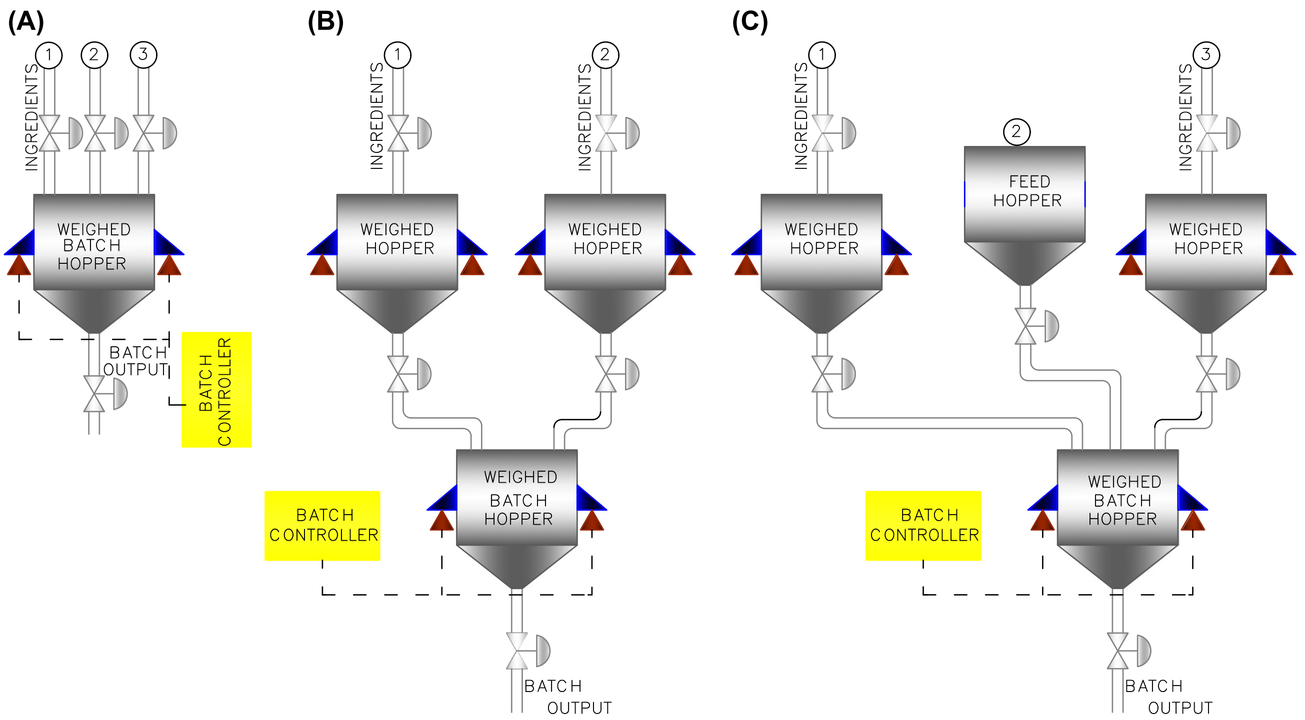


FIGURE VIII/1.0.1-2 Process batch weigher. (A) Cumulative type. (B) Simultaneous type. (C) Combination type.

electronics the automated system is preferred, nevertheless in some cases, especially in certain food processing industries, complete automation processes still are not preferred, hence semiautomatic systems may be used. The automated process is used mainly for recipes, batch sequence, inventory, and operation and maintenance management:

- Speed controls of feeding system as per material characteristics;
- Total flow quantity control of ingredients;
- In-line inventory control of output as well as ingredients used;
- Recipe control and optimization for different products;
- Diagnostics, operation, and maintenance management.

Considerations here are given to ingredient addition, etc. not complete batch processes involving, e.g., heating processing, etc. For further details on batch controls, Chapter VI of the author's book [2] may be referenced. The following industries apply this type of weigher:

- Food and beverage industry;
- Pharmaceutical;
- Chemical, e.g., soap and detergent;
- Mineral processing;
- Glass processing;
- Animal feed;
- Fertilizer;
- Rubber and plastics.

Two major issues to be noted in the figure are that there are two kinds of bins/hoppers used, one is a weighing bin/hopper directly connected with the batch control of the recipes, and the other is a feed bin/hopper. The feed hoppers are basically the same as the other hopper but are passive elements not connected with the control system directly (for weighing system) except its inlet/outlet valve operation.

Weighing hopper or batch hopper measurement is static and in one sense is level sensing, unlike in motion (motion of material with respect to the bin). There are three mainly kinds of process batch weighing systems, as clearly shown in Fig. VIII/1.0.1-2.

- *Cumulative type:* In the cumulative type, as shown in Fig. VIII/1.0.1-2A, there is only a single weighing bin and ingredients (in this case three) are weighed one after the other. Therefore, there are at least three weighing set points, e.g., for the first ingredient it will be for the weight of the first ingredient, the second set point would be the first + second quantities, etc. for all components. This continues until all ingredients have been weighed and the batch is discharged to the next stage, e.g., to a mixer. It is cheaper in the sense that there is one weighing system but it is slow and can be a less accurate system (errors in matching any set point can increase the inaccuracy).
- *Simultaneous type:* As shown in Fig. VIII/1.0.1-2B, there are separate weigh bins/hoppers for each component and each of the hopper outlets is controlled based on weight output. The final bin/hopper ensures the total set weight is achieved for discharging to the next stage. Here, better accuracy is expected and the process can be faster but is more costly.
- *Combinational type:* As the name suggests this is a combination of the above two processes, and is used, e.g., if the quantity of some ingredients are too small then it is possible to measure a small amount in the final batch weight hopper separately. The scheme has been depicted in Fig. VIII/1.0.1-2C.

2. **Gravimetric filling machine:** This is different from the process batch weighing system and is used for filling bags, drums, and containers. These are always used with a single feeding system and weighing single material. These are two types of gross/net weighers:
   - *Gross weigher:* Gross weigher machines fill different varieties of containers, such as bags, with a predetermined weight of product. It fills product directly into the bag to a preset weight without employing a separate weigh hopper prior to filling, e.g., bottles filled with product such as yogurt.
   - *Net weigher:* A common bag filling example is that of a cement bag filling machine. In net weighers/machines bags/containers are filled with a predetermined weight of product prior to placement in transport containers such as bags and drums. As only the material is weighed in a weigh vessel(s) before discharging to a container, these are called net weighers. There are three types as shown in Fig. VIII/1.0.1-1, and described in Table VIII/1.0.1-1.

TABLE VIII/1.0.1-1 Net Weigher Types

Types	Description	Application	Influencing Factor
Conventional	Feeds material to weigh vessel. Types of feedings are: Gravity gate; screw feeding; belt feeder, vibratory feeder	Widest application; depending on feeding type application varies	Inconsistency of material; bulk density; system vibration; speed variations, delay in cut of point response
Weigh out	First fills the material in weighing vessel then weighs preset value prior to discharge. So no flight compensation necessary	Same as above but may be with better accuracy	Variation of bulk density to affect loss in weight when materials are not free-flowing
Selective combinational	Several weighers in single machine for variety of products and weighers are used in combinations	For products with product variations	Vibration; multiple dump; parent–child issue

1.0.2 DISCONTINUOUS TOTALIZING WEIGHING SYSTEMS

These machines with a single feeding weigher are used to totalize discrete batch weights for the purpose of recording accumulated total weight of a larger bulk mass of material, and sometimes the throughput as well [1]. There are two types of the weighers: shipping and receiving weighers and in-process weighers.

1. **Shipping and receiving weighers:** These weighers totalize bulk material movements to or from a silo to a vessel such as a road or rail tanker, a barge, or a ship. They are used for bulk feed into a compartmented road or rail wagon and bulk transportation and shipping. Naturally, these have large capacities and may be >10 m.ton. Emptying or filling a large vessel can take many hours, involving a substantial financial transaction. Thus suitable protections to take care of power failure and mechanical breakdowns are needed [1]. Air displacement is an important issue to maintain accuracy of measurement, especially for cases for rapid filling and emptying the vessel when error may creep in.
2. **In-process weighers:** These are versions for use in various processes and manufacturing units, such as grain or rice milling. The weighing capacity is much less than that for shipping and receiving weighers, typically about 50 kg. Their primary use is to determine both the short- and long-term cumulative process weights of a product stream within a milling process [1] for assessing the milling efficiency of the product streams. Like in shipping and receiving weighers, air displacement is an important issue, if the air pressure built up during the emptying operation falls then the weigh hopper may be lifted, introducing error in measurement.

1.0.3 IN-MOTION WEIGHING SYSTEMS—DISCRETE MASS WEIGHING SYSTEM—WEIGHBRIDGES

In-motion weighing systems are of two distinct types: discrete mass weighing systems, such as road/rail weighbridges, and continuous weighing systems (mostly found in major processes and industrial plants). Of these two systems, discussions will be presented on discrete mass weighing systems in this section. Discussions on continuous weighing systems are in Section 1.0.4. In discrete mass weighing systems platforms are used. These systems are designed to note both the weight of the discrete mass as it passes over the weighing platform and accumulate a total weight. The measurement can be triggered either from the increasing weight on the platform or from an external trigger. Weighing coal wagons would involve weighing individual axle weights that are accumulated into individual wagon weights, and then the total train weight. To get the measure of coal, tare weights are subtracted. There are two main kinds: road weighbridges and rail weighbridges.

1. **Road vehicle weighing**: Normally, a road weighbridge comprises one or more weigh platforms designed to measure individual wheel or single axle loads as a road vehicle traverses the weigh platform(s). These weighbridges are required to measure efficiently; wheel, axle, and total vehicle load for commercial purposes, safety checking as well as checking for overload for road safety. There are two broad categories of road weighbridge, namely, weighbridges with civil foundations and weighbridges without foundations. These may be referred to as fixed and portable weighing in-motion systems, respectively [1]. The former is a permanent installation with the purpose discussed above, while portable systems are used for weight checks in random locations, frequently to detect vehicles avoiding permanent check sites and for overloading. Another kind is used to collect the data from a speeding vehicle, where sensors are embedded inside the road. Weighbridges are generally designed to measure the individual wheel or axle weights separately and summated if required to obtain the total vehicle weight [1]. Normally it is possible to weigh for any approaching vehicle in either direction but not for a *reversing* vehicle. There are

several measurement methods, the most common of which are:

- *Direct measurement:* This is used when the vehicle fits the platform. This is an accurate method of measurement. With the help of this it is possible to measure the tare weight and gross weight. The tare weight and gross weight must be recorded within 24 h so that weighing tickets for net weight can be generated.
- *End-and-end measurement:* This method is used for vehicle sizes not accommodated within the platform(s). As a result, two measurements have to be determined, one for the front and the other for the rear of the vehicle.
- *Axle load measurement:* This is used for measurements of the mass supported by separate axles, or groups of axles, of a vehicle.
- *Factors affecting measurements:* The following are the major factors affecting the performance of a weighbridge:
  - Speed of travel;
  - Mode of operation;
  - Site topography;
  - Road surface deficiencies.

  To end these discussions it is important to note that weighbridge weighing means (method) are guided by local government laws.

2. **Rail weighbridge:** To measure in-motion, the wheel, bogie, wagon, and total for commercial and safety reasons, rail weighbridges are utilized. Similar to road weighbridges, these also fall into two categories of rail weighbridge: rail weighbridges with civil foundations and those without foundations. These are often called *conventional type* and *foundation-less type*, respectively. There is also another type called the portable dynamic weighbridge.

   In rail weighbridges there are a number of strategically mounted detecting switches for detection and control of weighing. The major functions of these are listed here:

   - Detection of locomotives wherever they are positioned in the train for weighing computation;
   - Detecting the start and end of vehicles for correct axle and/or bogie weights;
   - Detecting the direction and speed of travel and initiating the weighing process;
   - Detecting when a train stops and rolls back, to avoid wagons being weighed more than once;
   - *Technical issues:* A rail weighbridge is a load receptor, inclusive of rails for turning over railway vehicles. The weighing may be finished in motion or in a stationary position. When a train which consists of a number of wagons goes through or over the load receptor, the load cells transmit the load assessment details to the control unit with the help of an analog to digital converter (ADC). At the similar time, the track controls send signals as to the type of motor vehicle passing over it. As a result, the control unit decides which values are to be acknowledged and which are not. The gross weights of the suitable wagons are displayed with the help of a processing unit (PU) on the video display unit (VDU). With the help of an operator station, the operator can input the wagon number, etc. An associated printer provides the weighing sheet;
   - *The major components are as listed below:*
     - A load receptor (load cells—hermetically sealed shear beam load cells/embedded strain gage type);
     - A few aprons;
     - Track switch;
     - Weighing electronics;
     - Indicating devices;
     - A printer;
     - A control unit.
   - *The key features include the following:*
     - It is a pitless design with minimum excavation;

- It has low cost on installation;
- High-accuracy weighing electronics, with proximity to track switches;
- Overspeed signal and alarm;
- Rollback detection;
- All types of four-axle/two-axle railway wagons, etc.;
- All types of locomotive removal;
- Auto/manual operation;
- Report generation;
- Digital link/communication facilities.

1.0.4 WEIGHBRIDGE LOAD CELL

The load cell is a common sensor required for all weighers, and hence short discussions on the same are presented here with special *reference* to weighbridges. However, further detailed discussions on load cells are also presented at later in this chapter also. Normally three kinds of load cells are deployed for weighbridges, these are described here:

1. **Single-ended beam cells:** These are cumbersome high-capacity single-ended bending beam load cells with four strain gages. In modern weighbridges these are not used often.
2. **Double-ended beam cells:** Double-ended shear beams provide a better mechanical solution than single-ended beams and the shear technology provides a product that is less susceptible to nonaxial forces. They require appreciable maintenance when used with a ball bearing.
3. **Canister:** Canister load cells have a long history in weighbridge applications and are considered to offer the best solution—provided they are well designed and built.

1.0.5 IN-MOTION WEIGHING SYSTEMS—CONTINUOUS SOLID FLOW SYSTEM

There are several kinds of devices and systems available for in-motion continuous weighing systems. These are regularly used in process plants, and hence need special attention. They are discussed at length in subsequent sections covering all the types of measurements shown in Fig. I/3.2.0-1, including nucleonic measurement. Overview of these are already covered in Section 3.2.0 of Chapter I and so are not repeated here.

Before moving on to actual discussions on continuous solid flow measurement, it is better to look into the mechanical equipment and material properties in subsequent discussions.

1.1.0 Discussions on Mechanical Equipment for Solid Flow

There are various pieces of equipment responsible for feeding and transporting of solids. This is applicable for all types of solids; be they in bulk form, or powder or granular form. In the case of fluid transportation, conduits such as pipes or ducts are used. In the case of solids various kinds of feeders are deployed for transportation and feeding. Like tanks and reservoirs for liquids, in the case of solid materials, silo hoppers, etc. are used as storage equipment. Also, in many cases air/gas is used for transporting materials. Naturally, in all such cases there will be two phases of gas and solid flow. Again the sizes of solid materials may vary from large chunk of materials to very fine powder materials. On account of these (e.g., two phase) it is not possible to use volumetric flow measurement instead mass flow are generally computed for solid materials. There are wide variations in material properties, which compel the use different kinds of feeding and transporting equipment. Therefore, prior to moving on to detailed discussions on these measurement systems, it is better to acquire some knowledge through brief discussions on the mechanical equipment used in solid material handling. With reference to Figs. VIII/1.1.0-1, the discussion starts with typical feed arrangement for solid materials in the above cluster of figures. In this connection it is worth noting that often conveyor and feeders are loosely used to mean the same set of equipment to transfer solids from one place to other. However there are functional difference as indicated in Fig VIII/1.1.0-2.

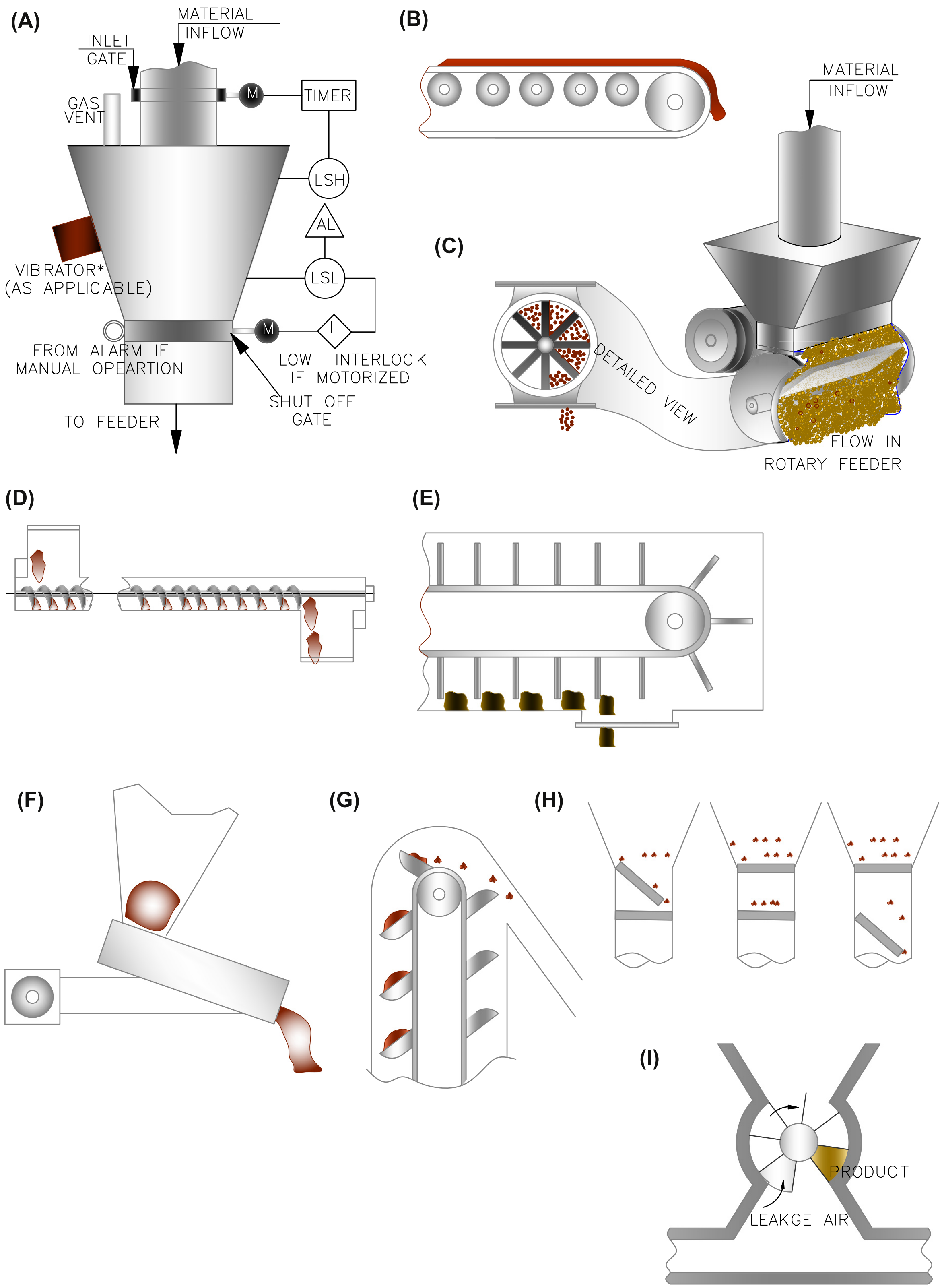


FIGURE VIII/1.1.0-1 Mechanical equipment for solid flow. (A) Feeding arrangement. (B) Belt conveyor. (C) Rotary feeder. (D) Screw conveyor. (E) Drag conveyor. (F) Vibrating feeder. (G) Bucket conveyor. (H) Double flap valve. (I) Rotary valve.

Conveyor/Feeder: *As the name implies, conveyor or conveyor system is a mechanical equipment and/or system used for material handling. The conveyor system is used to move solid materials from one location to another. When not covered Conveyors systems are used in applications involving the transportation of heavy or bulky materials. However with suitable covering/skirt the system could be used for fine solids also. Feeder is also a mechanical system to convey material in a controlled manner. The major differences between a feeder and a conveyor could be:*

Conveyors are not flood loaded and the speed of conveyors are fixed and speed are not controlled In contrast to that feeders are flood loaded and the speed of feeders are variable and could be controlled to modulate discharge rate.

FIGURE VIII/1.1.0-2 Conveyor/feeder.

1.1.1 FEEDING ARRANGEMENT FOR SOLID FLOW

Based on material properties there are a number of feeding arrangements for solid materials to flow. The feeding arrangement of cement from a cement silo, or raw meal feed from a raw material silo is an elaborate arrangement. On account of the material properties discussed later in this section, there will be possibility of materials becoming compacted, especially when there is a high moisture content. Also, in order to ensure flowability, it is necessary to have air blown to the systems, e.g., an air slide so that the material flowability is ensured for material extraction. Also for raw material conveying, there may be an intermediate bin/hopper from where the material is extracted and weighed before being fed to the system for example as raw meal to kiln. One of the simplest arrangements of material feeding has been taken for discussions and is shown in Fig. VIII/1.1.0-1A. We now investigate the functions of various components.

1. **Inlet gate:** Here, as can be seen, materials come to the hopper through an inlet section with an inlet gate which is motorized. The inlet gate is motorized because in the case of a high level being sensed by the level switch, it will close the inlet gate to stop the supply when the hopper level is high. Although not shown, there should be one high alarm so that the operator can take action. Here it has been made automatic through a timer (time setting done based on hopper capacity and flow rate).
2. **Vibrator:** In the case of solids with fine sizes there is the possibility of it becoming compacted and losing flowability. This may be more so in the case that there is the possibility of high moisture content (may come from raw materials in the open yard). In order to get rid of such situations, vibrators are mounted in the hopper so that materials do not stick due to the vibration effect. The frequency and duration of vibration needed are a function of the solid material size and characteristics. When the solids aerate easily, there may not be any need for a vibrator (but if there is a chance of compacting it is better to have the provisions for the same—in a cement factory in Jordan initially there was no such provision but it later added to get better results, especially during the winter season when there may be heavy snow fall).
3. **Outlet gate:** In the case of a low level the flow of material due to gravity may be affected, so at a low level the outlet gate may be closed to fill the hopper. Normally alarms are sufficient for operator action, however an interlock has

been shown to illustrate that here also automation could be implemented. Naturally, for implementing automation it is necessary that the outlet gate (which may be a pin type) be motorized, but it can be manual also. Closure of the outlet gate is necessary to prevent loss of the plug of material ahead of the succeeding feeding arrangement. Also, loss of a plug of deaerated material can cause production delays, because with new material there will be the need for fresh aeration.

4. **Gas vent:** Attention must be paid to the gas vent—this is necessary whenever materials are conveyed pneumatically. The vent should not be left open but may be connected to a bag dust filter and other dust-handling equipment.
5. **Hopper design:** Hopper design is another important aspect in solid flow measurement. A poorly designed hopper may yield improper flow, creating an arching rat hole in the hopper. This means that materials from all sides would not flow to the downstream conveying equipment, e.g., the belt feeder. The aim of the hopper design is to create "mass flow," so as to ensure uniform discharge from the bin so that material does not remain in the bin and bridge formation does not take place. If part of the material remains in the bin/hopper, it may become compacted and solidified. In poorly designed hoppers, such as "funnel flow" types, material will support itself and rat holes or bridging can occur [3]. A rat hole is a column of material flow inside, leaving material in the bin along the inside edges. Another issue is a bridge which is created when an opening occurs at the discharge of the bin, without an impact of the opening all the way to the top of the material pile. When material bridges take place in the bin, flow is stopped, additional material supplied to the bin can cause a breakdown or avalanche of material, creating an unstable disruption to the normal flow. A "mass flow" hopper design works in a first in, first out (FIFO) system, and so is very suitable for cases where aging or spoiling is a concern. These phenomena and designs are illustrated in Fig. VIII/1.1.0-3 and are further elaborated on in Subsection 4.1.2.2.

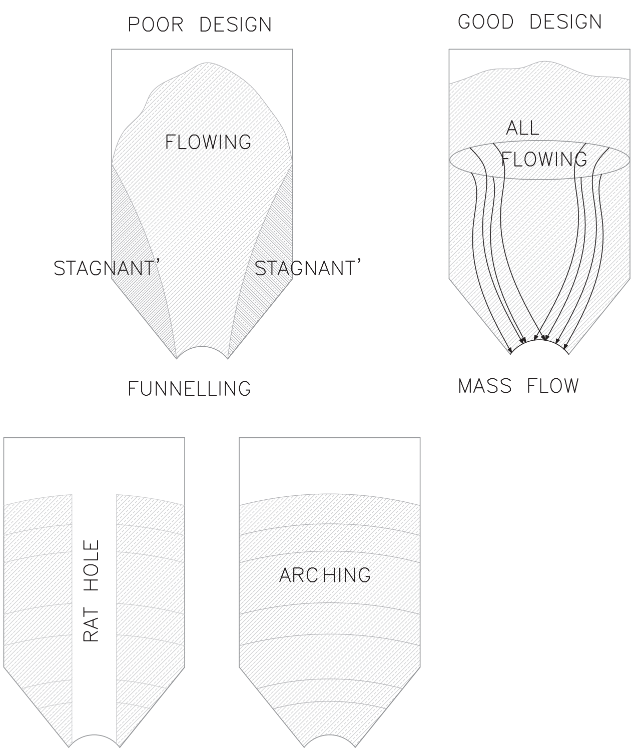


FIGURE VIII/1.1.0-3 Hopper design.

1.1.2 BELT CONVEYOR

Normally, a belt conveyor system uses two pulleys over which the belt moves continuously due to rotation of one of the pulleys, called a drive pulley. The other pulley moves due to movement of the belt over it. The belt is supported by a series of rollers/idlers along the path to prevent sagging of the belt due to the load on the belt. In this connection Fig VIII/1.1.0-2 may be referenced to have clear idea about its difference with feeder.

1. **Working principles:** Basically, a conveyor belt can be conceived of as a machine with a moving belt. A belt conveyor system consists of two endpoint pulleys complete with driving motor and necessary gear arrangement, a closed conveyor belt, and a set of other pulleys referred to as an idler and a few other accessories. The pulley that drives the conveyor belt rotating is called the drive pulley (also the transmission drum); the other is called the tail pulley. The drive pulley is driven by a motor complete with chain/V belt and reducer.

The operation of the conveyor belt relies on the friction drag between the drive pulley and the conveyor belt. In order to increase traction and ease out the drag, the drive pulley is generally installed at the discharge end and the tail pulley is located at the other end. The belt conveyor can be horizontal or inclined upward. Material is fed on the feed-side. The typical arrangement of a belt conveyor has been shown in Fig. VIII/1.1.0-1B.

2. **Major components:** Typically a belt conveyor consists of the following major components:
   - *Belt:* Made up of rubber and other materials like PVC, urethane, neoprene, nylon, nitrile, polyester, leather, etc. It has a specific defined width and length. This is sometimes referred to as a bed.
   - *Pulley:* A pulley is like an iron pipe, put on each end of the bed, and has a width the same as that of the belt or bed. A steel shaft of each pulley, passing through it, turns on a ball bearing. Thus, with the help of the drive and reducer, the shaft of the pulley turns on the ball bearing. The tail pulley is a freely moving pulley located at the tail end. One of these pulleys is shown in Fig VIII/1.1.0-1B.
   - *Drive:* One of the two pulleys is connected to a motor which runs at high speed of rotation. As the motor turns very fast, a speed reducer must be installed between the drive pulley and the motor. The motor is connected to the reducer with a V-belt or "C" face coupling.
   - *Toughed idler:* Between the two sets of pulleys there are idlers. The smaller roller type items shown just below the belt-carrying load are idlers. Idler rollers are either in sets of five, three, or two rolls. The belt conveyors can be flat or troughed belt conveyors in which the troughing angles can be from 15 to 45 degrees. In any case the belt should normally stretch over the idler uniformly. After discharging the load the belt returns back to the feeding end. The return belt also rolls over sets of idlers called a return idler.
   - *Take up screw:* There are take up screws at both ends of the conveyor to adjust the tension or stretch out in the belt. Adjustments on both sides should be the same.
   - *Tension tower:* For long and extra-long conveyors (motorized or hydraulically powered) take up pulleys are used to arrest belt sag and provide adequate tension through the length of the belt. These pulleys, along with auxiliary pulleys and accessories, are housed in a tension tower a few hundred meters away from the discharge end. They are normally hydraulically powered and controlled with take up pulleys used for cross-country conveyors for carrying limestone, coal, bauxite, or other mineral ores, etc. These conveyors may be as long as 10−15 km or even longer, normally pipe conveyors are used in such cases. In such an application multidrives (3−4) are deployed (could be with variable voltage variable frequency (VVVF) control on the discharge end). Tension control systems include the following:
     - Gravity towers;
     - Take-up winches;
     - Take-up trolleys;
     - Tension measurement devices;
     - Automatic tension control systems.
   - *Other components:* Other components related to belt conveyors are skirt, feeding chute, discharge chute, protection devices such as a zero speed witch, pull chord, etc.

1.1.3 ROTARY FEEDER

Rotary feeders are often referred to as an airlock device normally used in taking discharges from various silos, bins, or hoppers. In cement industries they find good applications. They can be classified either as feeders or air locks depending on the application; whether the regulated feed only is required or feed and air-tight boundary between upstream and downstream is required. In this section our point of interest is the rotary feeder. Airlock rotary valves are treated separately. To distinguish it is better to call this a rotary vane feeder. The sizing and shape of the pocket of the rotary feeder as shown in

Fig. VIII/1.1.0-1C are dependent on the characteristics of the material to be handled and the required flow capacity of the rotary feeder. Rotary feeders are meant for handling solids with smaller sizes and are not recommended for handling solids with large particle sizes or if the solids are sensitive to abrasion by the feeding device. On account of the relatively smaller size and high conveying capacity, rotary vane feeders find their applications for *metered* discharging of a wide range of free-flowing bulk materials at very high volumetric rates from conveyors or from stored quantities in bins, hoppers, or silos and suffer only a small amount of wear. This is one of the main issues for which rotary feeders find good applications in industries. There are low-cost versions of rotary feeders for dust feeding applications. Such rotary feeders are designed to be used in dust collection hoppers and other low-pressure applications. In such cases feeders may be directly connected to the motor through a gear box. Normally rotary vane feeders have either a circular or rectangular inlet casing made of cast iron or stainless steel. They have a horizontally mounted rotor with a certain number of V-shaped cross-section compartments, a drive unit, and a casing cover opposite the drive end. There are some gravimetric applications where a rotary-vane feeder is used in conjunction with a belt type gravimetric metering system. In such a case, the upstream rotary vane feeder is provided with a variable-speed drive with, e.g., a digital control system (DCS) to regulate the volume flow. In this application the rotary vane feeder is used as the volumetric feed section in instances in which the material is aerated or has a low bulk density. For optimizing performance it is important to select a suitable rotor speed.

1.1.4 SCREW CONVEYOR/FEEDER

The screw conveyor is one of the most versatile and cost-effective mechanical conveying systems, capable of handling not only dry solid materials but also semifluid materials. These screw conveyors are available in various configurations. The flour mill industry was probably the first to employ horizontal screw conveyors (or feeder) to convey corn and flour. It comprises of a screw mounted in an enclosed U-shaped trough. In some designs there will be an inclined rotating casing. There is a shaft-mounted screw rotating in the trough referenced above, and a drive unit for running the shaft, and there are helical blades attached to the driving shaft. The material is moved forward along the axis of the trough by the thrust of the screw thread or flight. As shown in Fig. VIII/1.1.0-1D, a discharge opening is provided at the bottom of the trough. The loading and discharging points can be located anywhere along the trough. Through a rotating motion, it delivers a fixed volume. The screw may have a single or several sections. The screw conveyors have support bearing at tough ends, but if the length is too long there may be the necessity for more in-between supports. Drive units of screw feeder could be variable-speed drives for feed control of low density or aerated materials [4]. For uses in cases of fluidizable materials, such as alumina, cement can flow uncontrollably in the conveyor, therefore, screw conveyors/feeders should have a large diameter with short pitch, i.e., short distances between blades. For handling sticky and highly viscous fluids, such as sewerage sludge, a single flight ribbon screw is a better choice to avoid material deposition at joints. The screw conveyor can handle materials from free-flowing to sluggish and it is very cost-effective when compared with belt, pneumatic, and aeromechanical conveyors. Screw feeders can be used in weighing the materials also, i.e., a screw weigh feeder.

1.1.5 DRAG CONVEYOR AND APRON FEEDER

1. **Drag conveyor:** Drag conveyors can handle a wide range of bulk materials. The versatile design, coupled with energy-efficient drive, makes it possible to have a small footprint, saving space for handling a high quantity of materials. It is also possible to handle materials for long distances of up to almost 100 m. A typical drag chain conveyor has been depicted in Fig VIII/1.1.0-1E. With the use of suitable materials and their treatments, it is possible for drag conveyors to handle most abrasive materials. Also, in a drag chain it is possible to use a suitable liner to handle various

kinds of applications. These are available both in flat or rounded bottom construction. It is possible to have an intermediate discharge so that multiple discharges are possible. It is supposed to be one of the best conveyors for dry free-flowing materials of different kinds. Clinker handling and chemical handling are popular applications of drag conveyors. The materials are static and only move en-mass by paddles or chains. It consumes less power and space than other choices.

2. **Apron feeder:** An apron feeder is another common feeder frequently used in many industrial applications. Apron feeders are used in conveying coarse bulk materials with fines, such as clinker, granulated blast furnace slag, or petroleum coke with crushers and reclaimers. They are also used for sticky materials. It is recommended that deep-drawn pan versions be used for these purposes. Other versions are also available. This can be used as solid flow also for solid flow measurements suitable load cell and speed sensor are necessary so that speed of the motor can be regulated to get controlled discharge e.g. cement side feeding or raw material feeding are examples of the same. An apron feeder consists of a stand of endless tractors made up of cast/fabricated steel pans bolted to link each stand. The chains are driven by a drive (speed control for weighing), connected to the chain through a reducer and sprocket at the discharge end. The pans travel with a chain and roll over the head sprocket to discharge materials.

1.1.6 VIBRATING FEEDER AND TABLE FEEDER

Vibrating feeders and table feeders are two kinds of feeders regularly encountered in many industries, including the pharmaceutical industries.

1. **Vibrating feeder:** In vibrating feeders, vibration is one of the motive forces for material movement. In a vibrating feeder, vibration and gravity forces are used to move materials. In the principles of operation, the oscillating motion of the feeder/screen is imparted by the unbalance masses mounted on the extended shaft of the two motors rotating at the same speed but in opposite directions. These motors are placed symmetrically about a line at right angles to the motor base and pass through the center of gravity of the frame. Therefore, there will be a resultant force, on account of the unbalanced mass passes, to create displacement in either direction. The total displacement in either direction is called "stroke" [5]. Vibrating feeders are used where products are to be fed either continuously or in batches, such as despatching bulk materials from bins, feeding crushers, mixers, or conveyor belts, bucket elevators, vibratory screens, and loading and sorting plants. A trough is provided with wear-resistant liners which do not influence the quality and character of the product they handle. The slope and strokes are adjustable. The motors are an important component and should have good enclosure class, e.g., IP55, and the winding should be vibration-proof. A typical vibrating feeder is shown in Fig VIII/1.1.0-1F. The following issues are important for the sizing and design of the equipment:
   - Bulk density and particle size;
   - Inlet/outlet discharge conditions for the equipment, including placement of material on the feeder;
   - Application area and purpose, i.e., whether it is a batch process or continuous process, and also whether feeding equipment is a belt conveyor, bucket elevator;
   - Dimension of incoming stream of materials.

   The correct drive selection is very important for efficiency, long life, and low operating cost.

2. **Table feeder:** A table feeder is used in many industries including pharmaceutical industries, and typically consists of a power-driven circulated plate rotating directly below a hopper/bunker. There will be a feeding collar immediately above the rotating table used in conjunction with an adjustable plough, to determine the volume of material discharged.

   The major components of a rotary table feeder are described here.

   The table will be fabricated thick SS/MS plates.

- Driving motor with reducing gear arrangement;
- Adjustable plough assembly;
- Guard ring assembly.

1.1.7 BUCKET CONVEYOR

Bucket conveyors, similar to the one shown in Fig VIII/1.1.0-1G, are also known as bucket elevators. Bucket conveyors/elevators are designed for use in the transportation of powders or bulk solids of various kinds, vertically/steeply inclined plane even in a horizontal plane—but in a single plane. They use an endless belt or chain with a series of buckets attached to the belt or chain. Bulk materials are put through an inlet hopper. Buckets (or cups) dig into the material and convey it up and over the head sprocket/pulley, and then throw the material out through a discharge throat. Bucket feeding is done at a controlled rate. The buckets are returned back down to a tail pulley or sprocket at the bottom. Bucket conveyors/elevators are available in a variety of shapes, weights and sizes, and classes. Broad classification and description of bucket conveyor/elevators have been described here:

1. **Centrifugal bucket elevator:** Of the various bucket elevators, centrifugal bucket elevators are the most common. They are deployed to convey all free-flowing, powdered bulk solids, such as grains, animal feed, sand, minerals, sugar, aggregates, chemicals, etc. They operate at high speeds, which throw the materials from the buckets into discharge throats by centrifugal force.
2. **Continuous bucket elevator:** As continuous bucket elevators operate at slower speed, they can be used for handling friable, fragile materials because they minimize product damage or are used to handle light fluffy materials where aeration of the product must be avoided. On account of the continuous bucket placement, the force of gravity can be utilized for discharging load onto the inverted front of the proceeding bucket. The bucket then guides that material into the discharge throat on the descending side of the elevator. Because every bucket application is unique, selection of the proper type of bucket elevator depends largely on the capacity requirements and the characteristics of the material.
3. **Positive discharge elevators:** Except two distinguishing features, positive discharge type bucket elevators are similar to the centrifugal discharge elevators. The buckets are spaced at a regular pitch and mounted on two strands of chains, and are provided with a snub wheel under the head sprockets to ensure inverting of the bucket for complete discharge. The speed of the bucket elevators is slow. These are quite suitable for handling light, fluffy, dusty, and sticky materials. The feeding is done by the digging of the buckets.
4. **Horizontal discharge:** These are mainly used to handle granular materials such as in flour mills, animal feed, etc., for transferring the materials into silos. These are often used in mineral-handling applications in vertical/inclined and horizontal planes. Generally they are made from steel and are used for high-capacity material handling.
5. **Major parts:** The major parts/components of bucket conveyors/elevators include the following:
   - Head;
   - Cover;
   - Belt/chain;
   - Bucket;
   - Drive unit;
   - Reducing unit.
6. **Major application areas:** The following are the major application areas of bucket elevators:
   - Ammunition/explosives;
   - Animal feed;
   - Bottle caps/fasteners;
   - Frozen food products;
   - Grains;
   - Capsules/tablets;
   - Cement plants;
   - Carbon black;
   - Coal/sand/clay/lime;
   - Tobacco;
   - Dry chemicals.

1.1.8 DIVERTER GATE VALVE, DOUBLE FLAP GATE, AND ROTARY AIRLOCK VALVE

A few other pieces of equipment, like diverter gate valves, double flap valves, and rotary airlock valves that are used frequently in solid material-handling systems are briefly discussed below.

1. **Diverter gate valve:** A diverter gate valve is used for the selection of outlet ports in solid material handling by the position of the diverter flap. Diverter valves are designed to direct product flow outlets of storage bins, silo conveyors, gravity flow chutes, and other discharge points. These valves are available with three-positional control on the diverter. An intermediate position can be used for splitting the flow. Technical details and major application areas are as follows:
   - *Technical details:* Since it may have to handle falling abrasive materials, it has to be very rugged in design. Normally, they are made up of MS casing but other materials can also be used depending on the application. There can be a lining based on the application and material characteristics. CS and SS are common materials used for valves. Such diverter valves can be manual and/or be with an actuator, which can be electric or pneumatic.
   - *Application:* As the name suggests, it is used to determine the outflow of bulk, free-flowing material from a bin/hopper, bag filter, silo, etc. Cement, chemicals, mining, mineral process, textile, paper, food grains, and other industries use them.
2. **Double flap valve:** Double flap valves are used for achieving airlock sealing with controlled feeding. These valves consist of two independent flap valves mounted one upon the other, with their opening and closing alternated and synchronized to ensure that only one valve opens at a time, as shown in Fig VIII/1.1.0-1H. The upper valve chamber holding volume and the rate of operations determine the throughput of the valve. These are slow-operating valves, and thus show a batch feeding pattern. The selection of cone or flap depends on the characteristics of the material to be handled and the system requirement, such as pressure sealing. The cone valves usually have a round opening, whereas flap valves can have square openings.
   - *Technical details:* Normally MS are used for fabrication of these valves, but other materials are also possible. These valves can have liners to handle corrosive and abrasive materials. Flap valves can be of different inlet sizes from 200 to 500 mm. Double flap valves only leak due to the volume of high-pressure air trapped between the two flaps after the bottom flap has opened and closed. The gas between the two flaps can be purged if necessary before actuation. Valves are closed by a counterweight normally, so they require power only for opening. The valves are normally available with both electric and pneumatic actuators and are connected to DCS for control and operations.
   - *Applications:* Double flap/cone valves are used for extracting bulk material from bins, which are maintained at a pressure different to the external pressure. The bottoms of ESP hoppers and bag house hoppers are typical locations for these valves. As the valves can handle fine dusty or grainy materials, such as cement, crushed ore, sugar, minerals, grains, plastics, dust, fly ash, flour, gypsum, lime, coffee, cereals, pharmaceuticals, etc., they find their applications in industries including cement, steel, power, chemicals, mining, mineral process, textile, paper, food grains, etc.
3. **Rotary airlock valve:** Rotary airlock valves are used in bulk handling systems for free-flowing dry powder, granular, crystal or pellet forms of materials. Rotary airlocks are suitable for fitting below a chain conveyor/screw

conveyor/hopper/silo/bag filter/ESP/bin, etc. Two major functions of rotary airlock valves are to seal and prevent the possibility of back flow of material in a pressurized system and to provide a rated drop-through discharge. The volume of the "V chamber" and the speed of operation determine the capacity of discharge of rotary airlock valves. Material density, material flowability, and desired capacity are major issues for the design of rotary airlock valves.

- *Technical details:* Rotary airlock valves are available in different sizes from 200 to 900 mm, to accommodate material capacities of over 300 tons/h (TPH). DEMECH can supply rotary airlock feeders from 1 TPH to 300 TPH capacity and inlet sizes ranging from 200 to 800 mm in round or square shapes. Generally, rotary airlock valves are made up of MS, but other materials are also used. They are also available with a hard lining. The vane edges are provided with replaceable tips of flexible material, such as spring steel, to achieve a good sealing. These are normally available with a motorized actuator with a reducer either in direct coupling or chain arrangements.
- *Applications:* Rotary airlock valves are used for handling various materials—typically, cement, ore, sugar, minerals, grains, plastics, dust, fly ash, flour, gypsum, lime, coffee, cereals, pharmaceuticals, etc. Thus they find their applications in industries like cement, chemicals, mining, mineral process, textile, paper, food grains, power, etc.

1.1.9 MISCELLANEOUS MECHANICAL EQUIPMENT AND DEVICES

Apart from the various pieces of equipment discussed above, there are a few other equipments and devices used for solid material handling, such as shaker feeders, roller feeders, etc. There are other devices also necessary for regulating solid flow and maintain pollution. Such devices include but not limited to dampers and bag dust collectors of various kinds. At each transfer point in solid material handling, especially for fine and powder solids, bag dust filters are used. There are various bag dust collector designs, such as regular hopper entry, tangential entry, etc. Also, they contain a bag dust collector with pulse jet online/offline types. There are different kinds of dampers, i.e., nonreturn flap, guillotine damper, biplane damper, biplane damper, Louvre damper, butterfly damper, and coffee pot damper. These dampers can be manual or actuator-operated. Actuators may be pneumatic or motor-operated.

With this the discussions on mechanical equipment come to an end, so as to look into the details about material characteristics which are very important for solid flow measurement.

1.2.0 Material Characteristics for Solid Flow

The discharge flow patterns of feeders/conveyors vary with material characteristics as well as discharge type, style, and conveyor speed. In the case of solid flow, size and material characteristics are very important issues in selecting the conveying equipment and flow measurements. When the material sizes are large there may be a problem with its discharge, weight, etc., because when they are discharged from a height it may cause problem, e.g., there could be an issue with ripping of the belt due to sharp edges or an issue related to getting stuck at any transfer or discharge point. However, such issues are rather simpler to tackle. More problems may come from very fine/powder solids. Apparently they show good flowability but the material characteristics play a great role in flow and flowability. This will be clear from an example; materials like sulfur become compacted very quickly, even under normal conditions, in contrast, many other materials become compacted only under pressure due to a heavy load (weight of the material) in the storage space. When fine materials become compacted their flow from storage will not be uniform, unless some external means, such as a vibrator or fluidizing by air, is applied to them. A granular free-flowing material, e.g., wheat/sugar will flow smoothly off a conveyor even at

low speeds. Meanwhile other materials, for example, sulfur, with a higher possibility of becoming compacted, or materials with a high angle of repose, may drop off in a nonuniform pattern or even in lumps, especially at low speed. From these examples it is clear that as with fluids in cases of bulk/powdery materials, there is a necessity for some shearing forces. In this section brief discussions will be presented on material characteristics and associated influencing factors. These will help in understanding the necessity for variations in equipment type and styles covered in the above section.

1. **Solid flow properties:** The solid flow properties depend on several parameters, including the following:
   - *Particle shape and size:* Varies from needle-like to spherical, dependent on sphericity, equivalent volume/surface diameter, etc.;
   - Particle size distribution is important for the strength of bulk solids;
   - Chemical composition of the particles;
   - Moisture content (liquid bridge);
   - Temperature.

   Some of these properties are discussed later. Theoretically it is not possible to determine the flow behavior of solids and their dependence on various parameters indicated above. Such dependences are determined with the help of a suitable testing arrangement.
2. **Uniaxial compression test:** The flow of solids in powder or fine forms is rather complex. For bulk solids "flowing" means that a bulk solid is deformed plastically due to the loads acting on it (e.g., failure of a previously consolidated bulk solid sample). The magnitude of the load necessary for flow is a measure of flowability. As discussed above, theoretically it is not possible to determine flow behavior, so these need to be demonstrated first with the uniaxial compression test. If a hollow cylinder filled with a fine-grained bulk solid is compressed vertically, one will observe that with an easy-flowing, dry bulk solid with large, hard particles, i.e., wheat grains, the bulk density will increase very little. With a fine and/or moist bulk solid (e.g., flour, moist sand), one will observe a clear increase in bulk density. In addition to the increase in bulk density from consolidation stress, one will also observe an increase in the strength of the bulk solid specimen. Hence the bulk solid is both consolidated and compressed through the effect of the consolidation stress. After this, if the bulk is relieved of the consolidation stress and then again the cylindrical bulk solid specimen is loaded with an increasing vertical compressive stress, the specimen will break (fail) at a certain stress. The stress causing failure is called compressive strength. In bulk solids technology one calls the failure "incipient flow," because at failure the consolidated bulk solid specimen starts to flow. The bulk solid dilates somewhat in the region of the surface of the fracture, since the distances between individual particles increase. From here one can infer that incipient flow is a plastic deformation (refer to Chapter VII) with a decrease in bulk density. In addition to consolidation stress, consolidation time is also important.
3. **Time consolidation (caking):** Some bulk solids, such as sulfur or garlic powder, continue to gain strength if stored at rest under compressive stress for a longer time interval. This effect is called time consolidation. The following issues are responsible for time consolidation [6]:
   - Solid bridges due to solid crystallizing when drying moist bulk solids, where the moisture is a solution of a solid and a solvent (e.g., sand and salt water);
   - Solid bridges from the material itself; and after some material at the contact points have been dissolved by moisture, i.e., crystal sugars with slight dampness;
   - Bridges due to sintering during storage of the bulk solid (temperatures very near melting point), e.g., some plastic materials;
   - Plastic deformation at the particle contacts, hence there is an increase in adhesive force and larger contact area;
   - Chemical processes/reactions;
   - Biological processes (e.g., due to fungal growth).

In the next section, various forces and their actions on bulk solids are discussed.

1.2.1 FORCES AND STRESSES IN BULK SOLIDS DURING FLOW

In this section the changes in bulk solid characteristics with applied forces and stresses are discussed to give idea about the material characteristics of the same.

1. **Stress in bulk solids:** In the case of bulk solids, flow behavior may be similar to that for a fluid, but it cannot be analyzed as a Newtonian fluid. This is very clear from a simple example; if the bulk solid were to behave like a Newtonian fluid, the stresses in all directions would be equal in magnitude but in reality it is not be so for a solid material. In bulk solid materials, on account of vertical stress from the top there will be stress in the horizontal direction also and such stress will be less than the vertical stress. As vertical stresses are increased the interparticle space will tend to change and horizontal stress will develop. Also, it can be observed that in a bulk solid different stresses can be found in different cutting planes. This behavior shows that bulk materials cannot be treated as fluids and instead bulk materials are analogous to solids. Thus the behavior of a bulk solid is quite different from that of a fluid. Stress conditions in solids at different planes can be found with the help of a Mohr's circle as explained in Fig. VIII/1.2.1-1. The procedure for finding the stress conditions at different planes is available in any standard book on mechanics.
2. **Adhesive forces:** Adhesive force is very predominant in bulk solids, so, in the case of bulk solid materials, this force plays an important role in the sense that flowability of the bulk materials will be affected on account of the adhesive forces between individual particles. For fine-grained, dry bulk solids, the flow properties are mainly influenced and guided by adhesive force due to the deforming force for fine-grained solids, popularly known as van der Waals interaction adhesive force and liquid bridges. *Liquid bridges* are formed by small regions of liquid in the contact area of particles, in which, due to surface tension effects, a low capillary pressure prevails to create the adhesive force. In addition to liquid bridges, van der Waals' cohesive forces can also occur from electrostatic and magnetic forces. Both adhesive forces are dependent on particle size and on the distance between particles. Therefore, one may conclude that the reason for an increase in flowability of bulk solids with an increase in particle size is due to adhesive force. Conversely, it can be said that with a decrease in particle size the strength of bulk solids increases. The flowability of bulk solids also depends on the relationship of the adhesive forces to the other forces acting on the bulk solid. The outside compressive force acting on a bulk solid element can increase the adhesive forces. This mechanism is used, e.g., in the production of tablets or briquettes [6].
3. **Wall friction:** Wall friction is the friction between a bulk solid and the surface of a solid, i.e., the wall of a silo/hopper/bin. The wall

Mohr's circle: *Mohr's circle indicates the principal angles (orientations) of the principal stress in solids. It is a graphical representation of plane stress strain conditions. With the help of Mohr's circle the stress components can be found, i.e., the coordinates of stress point on the circle, acting on the plane passing through it.*

FIGURE VIII/1.2.1-1 Mohr's circle.

friction angle or coefficient of wall friction plays an important role not only for storage vessel design but also for solid flow. Based on the wall friction angle, depending on the required discharge, decisions are taken during vessel design, whether or not the polishing of the wall surface or the use of a liner has advantages in the flow of the bulk solid [6]. Even the shape of the wall of a storage vessel may be influenced by the wall friction coefficient.

With this idea of the various forces acting on particles, it is time to look into the flowability of bulk solids, especially fine particle solids or powdered materials.

1.2.2 FLOWABILITY OF BULK SOLIDS

From the above discussions, it is clear that the physical properties and characteristics are extremely important for flow of granular bulk solids. Also, it has been noted that not only handling equipment but also storage of materials is important for bulk solid flow.

Definition of flowability: Like fluid flow, powder and fine bulk solid flow is complex and multidimensional and is highly dependent on bulk solid *characteristics*. On account of this it is not possible to *quantify* flowability by any single test nor is it possible to express the same as a single value or index. In fact, flowability is not an inherent material property at all [7]. Both physical properties of material affecting flow and the equipment used for handling, storing, or processing the material are responsible for the flowability of powder or fine-grained bulk solid materials. Thus it is needless to argue that equal consideration should be given to both the material characteristics and the equipment. Therefore, a more accurate definition of powder flowability is the ability of fine solid materials to flow in a desired *manner* in a *specific* piece of equipment. In view of this, the loosely used term *free flowing* becomes meaningless unless the specific equipment handling the material is specified [7]. The specific bulk characteristics and properties of a powder that affect flow and that can in principle be measured are known as *flow properties*, e.g., cohesive force and wall friction as discussed above. From the above discussions it transpires that there are two factors, one is equipment associated with solid flow already covered in Section 1.1.0, also various forces related to flow have been covered in Section 1.2.1. Now discussions will be on various other properties related to flowability.

1.2.3 PROPERTIES FOR FLOWABILITY OF BULK SOLIDS

The storage, handling, and flow of bulk solids, especially fine materials, are important in all industries, especially for agricultural, cement, ceramic, food, chemical, metallurgical, mining, pharmaceutical, and other bulk solids and powder-processing plants. Flow is defined as the relative movement of a bulk of particles among neighboring particles, or along the wall surface of a container (Peleg, 1977). Since flow properties and bulk material storage, handling, and processing equipment go hand in hand to achieve the desired flowability, it is important to gather some knowledge on the various parameters, such as angle of repose, bulk density, angle of internal friction, cohesion, and compressibility, etc. In this section these points shall be discussed. This discussion supplements the discussions presented in Section 1.2.1.

1. **Angle of repose:** As already indicated in Fig. I/3.2.1-4, the angle of repose (AR) is defined as the angle between the horizontal and the slope of a heap of granular material dropped from some designated elevation. The angle of repose is very much qualitatively related to the flow properties of that material, and is a direct indication of potential flowability. The angle of repose of a bulk solid can be described using the following equation:

$$\tan\varnothing_r = an^2 + b\cdot\frac{M}{D_{av}} + cs_g + d \quad \text{(VIII/1.2.3-1)}$$

where $\varnothing_r$ is the angle of repose (degrees); n is shape factor based on specific surface (−);

M is moisture content (db %); D_{av} is average particle diameter (cm); s_g is specific gravity (−); and a, b, c, and d are empirical constants. From the above equation it is worth noting that with an increase in moisture content the angle of repose increases. The angle of repose is related to the bulk density and surface area, etc. From the study of documents in pharmaceutical industries where flowability and angle of repose for powders are tested it can be seen that an angle of repose between 25 and 30 degrees gives excellent flow behavior and between 30 and 35 degrees it is good but starts worsening above 40 degrees and above 50 degrees it is poor.

2. **Bulk density:** The bulk density of granular solids and powders is not only important for determining the volume of transport/storage vehicles but is also important for flowability of materials. From the discussions in Subsection 1.2.0.2 it has been noted that bulk density is a function of both particle size as well as handling and processing operations. Bulk density also depends on moisture and chemical compositions. Bulk density is defined as the mass of particles that occupies a unit volume of a container. Increases in bulk density have been observed when conditioners are added (Peleg and Mannheim, 1973; Hollenbach et al., 1983), which results in modification of density by lowering the interparticle interactions [8]. The bulk density of many materials, such as food powders, decreases with an increase in the particle size, as well as with an increase in equilibrium relative humidity. Porosity, which is related to bulk density, can be expressed as the percentage of voids in a bulk solid:

$$P(\%) = (V - V_p) \cdot 100/V \qquad \text{(VIII/1.2.3-2)}$$

where P is porosity (%); V is bulk volume of the bulk (cm^3); and V_p is particle volume of the bulk (cm^3). P is affected by the flow of the granular material. As porosity decreases, bulk density increases (Sjollema, 1963).

3. **Frictional force:** A measure of the force required to cause particles to move or slide on each other can be obtained from the internal friction, i.e., the angle of internal friction. Stable slopes in bins are highly dependent on the angle of internal friction (Johanson, 1971/72). Particle surface friction, shape, hardness, size, and size distribution are major issues and influential factors for internal friction. Angle of internal friction data are an important parameter for the design of gravity flow bins and hoppers (Mohsenin, 1986; Rao, 1992). This is already discussed in Section 1.2.1 also in connection with wall friction.
4. **Compressibility:** Much attention has been given to the behavior of bulk solids under compressive stress and this has already been covered in Subsection 1.2.0.2. This is a very important factor for flowability.

   There are a numbers of other factors which also influence the flowability of bulk solids/fine powders and these will be covered in the following section.

1.2.4 FACTORS INFLUENCING FLOWABILITY OF FINE BULK SOLIDS

Flowability is a factor for several processes in process and industrial plants. This will be clear from an example. In the pharmaceutical industry blending is tremendously important for the final blend. This blending not only depends on the type of blender used but also on the flow behavior of the powder during the blend cycle. Therefore, the importance of flowability and associated factors affecting it cannot be overestimated.

From earlier discussion it has been established that flowability of powder/fine granular bulk solids is a consequence of the combination of a material's physical properties, the equipment used for storage, handling, and processing these materials, and environmental conditions. In this section brief discussions are presented on these and other environmental factors.

1. **Particle size:** As indicated in the initial discussions, particle size and particle size

distribution have a direct significant effect on flowability and other properties like bulk density, angle of repose, and compressibility of bulk solids (already discussed). Also, it has been discussed that a reduction in particle size often tends to decrease the flowability of a given granular material due to the increased surface area per unit mass [8]. An increase in particle size generally leads to an increase in compressibility with lesser changes in bulk density.

2. **Moisture:** With moisture absorption, materials often show increased cohesiveness on account of liquid bridges, as discussed earlier. According to Johanson (1978) moisture content thus affects the cohesive strength and arching ability of bulk materials. Moisture often modifies the physical properties of a material and can behave differently. This will be clear from two examples from Ref. [8]: the angle of internal friction of zinc ore was found to be 32 and 56 at 18% and 23% moisture contents, respectively [8]. Also the unconfined yield strength of sugar increased sevenfold as the moisture was increased by only 3% [8]. From the discussions one could infer that with an increase in moisture, the bulk density of granular solids generally decreases and the compressibility increases.
3. **Humidity:** The relative humidity of the air is an environmental factor, influencing material storage in bins/hoppers or silos, because humidity affects bulk material properties. Many bulk materials are hygroscopic and thus the exposure to higher humidity results in increased moisture content in the bulk materials. As a direct consequence of this there will be an increase in the bulk strength and angle of repose, and hence a decrease in flowability. Therefore, one can conclude that there will be a significant effect on the cohesiveness of granular powders, and so the flowability will be reduced. When the materials are stacked outside, as the author faced in Jordan (for limestone shale stacks), then during winter the materials used to absorb a lot of moisture (especially for snow/rain fall) and hence raw meal feed was a serious issue from a flowability point of view. In all intermediate storage hopper vibrators were installed to extract materials which during summer days were easy flowing.
4. **Temperature:** Temperature also has a substantial effect on bulk solid flowability. The most drastic temperature effect is the freezing of the moisture contained within the granular materials and on particle surfaces [8]. Therefore, whenever possible the materials should be kept at a temperature around 30°C above freezing to avoid the adverse effects of temperature on flowability. Caking effect can occur when there are changes in crystallinity or other properties due to temperature variations. Also, the temperature of the wall and bulk material may change the friction angle.
5. **Pressure:** Compacting pressure is also an important factor that affects the flow properties of bulk solids. The bulk may be subjected to compaction on account of the pressure impact from a falling stream of solids during silo filling and/or external loading. The effect of pressure on flowability of powders is twofold [8]:
   - Higher pressure may lead to a larger number of contact points between particles, and hence more interparticle adhesion.
   - Increased compaction produces a significant increase in critical arching dimensions and overpressure effects are nonlinear, and hence vary significantly with the sample.
6. **Anticaking flow conditioner:** According to BarbosaCanovas and Yan (2003), caking is defined as being when two or more macroparticles, each capable of independent translational movement, make contact and interact to form a congregate in which the particles are incapable of independent translations [8]. To improve flowability, at times anticaking agents are commonly used as additives to assist a powder in maintaining a steady flow and/or to increase its flow rate. Flow conditioners are chemically inert substances which are added for a similar effect.
7. **Fluidization:** This is often used to increase flowability or for fluidized-bed processing

which shall also include processes such as granulation and drying. In cement plant, pharmaceutical plants such phenomenon is common. Material extraction from raw meal silo or cement silo fluidization is adapted for extraction of fine materials from tall silos.

8. **Fat content:** This is mainly applicable for organic food, food grains, etc. Free surface fat is expected to play a key role in granular flowability but has not quite been established.

One may conclude that flowability of fine granular solid materials is extremely important for most industries. In the case of the pharmaceutical industry it is essential to ensure consistent feed at all times, i.e., separation of a small quantity of powder from the bulk for the creation of individual doses such as during tableting and vial filling, feed consistency to and through the equipment governs the uniformity of weight of the dose [7] and so is an absolute necessity. Material testing is critical for successful delivery of an engineered solution to meet the specific requirements of powder or fine granular bulk solids handling needs. As stated earlier, to obtain the correct material properties, testing is done. However, this is purely a part of the design of the material-handling system and so no further discussions are warranted from an instrumentation point of view.

With this the discussions on material characteristics come to an end. The discussions in Chapter I Section 3.2.0, where principles of operation of various kinds of solid flow meter types have been described, should be recalled to see how different instrumentation technologies are deployed to measure various kinds of solid flow. With the primary knowledge on various meter types and mechanical and material details it is better to compare various technologies deployed for solid flow measurements so that the intricate details of various solid flow meters discussed in subsequent sections will be meaningful to the reader.

1.3.0 Evaluations of Various Technologies for Solid Flow Metering

There are several ways and means for solid flow measurement in process and industrial plants. In the subsequent sections these will be discussed at length, i.e., discussions on in-motion weighing systems—continuous solid flow systems as mentioned in Section 1.0.4. There are many technologies involved in such measurements, such as weighing feeders, solid flow meters, and radiation type measurements. The discussion starts with weighing feeding systems and their comparative studies.

1.3.1 COMPARISON OF VARIOUS WEIGH FEEDER TYPES

The option of flow measurement while feeding or conveying is always preferred. In order to address such an issue several weigh feeder types are used. These can be a belt scale/belt weigher, weigh feeder, apron weigh feeder, or screw weigh conveyor (feeder). Both the belt scale/belt weigher and weigh feeder use a belt conveyor in conveying material with the only difference between them being the control of drive speed. In the case of a belt scale/belt weigher, it is used for feeding/conveying with a provision for measurement of solids conveyed without any control on the conveying materials, i.e., there is no control of feeder speed. In contrast, in the case of weigh feeders, they have driving motors used with a suitable and sophisticated drive speed control system to feed or convey a metered quantity of solid materials — as already indicated in Fig VIII/1.1.0-2. As already discussed in Section 1.1.0, screw conveyors and apron feeders have different ways and means to convey materials. In these cases it is also possible to measure and even control the quantity of materials conveyed. Therefore, these are called screw weigh feeders and apron weigh feeders, respectively. Table VIII/1.3.1-1 compares weigh feeding systems, showing the various pros and cons of different weigh feeding systems.

TABLE VIII/1.3.1-1 Comparison of Weighing Systems

Issues	Apron Weigh Feeding	Belt Weigh Feeding	Screw Weigh Feeding
Features	• High temperature with-stand capability. Temperature up to nearly 700°C • Used for bulk materials with fines and sticky materials	• Flexible design with varying width and length • Capable of handling wide varieties of materials • Available in open and closed versions	• Can be totally sealed and well applied for sanitary applications • Flexible in length; compact in design with short footprint
Capacity	Capacity ~2500 t/h	Capacity ~850 t/h	Capacity <300 t/h
Challenges	• Too many moving parts hence maintenance prone • Large area required as it has larger footprint	• Spreading and spill over the belt is of concern • Uniform distribution of material is important for proper accuracy hence off-center loading is challenging	• Build up on flange reduces accuracy • Limited capacity available

1.3.2 COMPARISON OF VARIOUS SOLID FLOW METERS

I am very tempted to quote the famous saying of Matt Morrissey, Product Manager, Weighing Technology Siemens; "Solid flow meters are interesting solutions to indicate flow rates in pipe and chutes." According to him these flow meters are as good as the whole process around them [9]. There are a number of solid flow meters, such as the impact flow meter, centripetal flow meter, Coriolis flow meter, capacitance flow meter, and microwave flow meter. In this section short discussions are presented on these. Impact and centrifugal flow meters are very similar. In impact scale, normally the horizontal component of the impact force is measured either by LVDT or load cell. In a centripetal flow meter the guide is parallel to the sensing plate and the tangential force exerted on the load cells. Other meter types are the Coriolis meter and microwave meter whose working principles have already been discussed in Chapter I and so are not repeated here. There are some other flow meters for solid material, i.e., capacitance and force flow types, both of which use double sensors to complete measurements. A capacitance solid flow meter is a low-accuracy flow meter, while a force flow sensor requires very precise alignments and is maintenance prone. These two flow meters are not very popular in solid flow metering. A short comparison of these meters has been presented in Table VIII/1.3.2-1.

TABLE VIII/1.3.2-1 Solid Flow Meter Comparison

Meter Type	Accuracy	Flow (t/h)	Flow Type	Maintenance	Feature
Centripetal	±0.5% AR	1–35	Gravity	Moderate	• Dust-tight • Accuracy unaffected by change of bulk density • Build up reduces accuracy

Continued

TABLE VIII/1.3.2-1 Solid Flow Meter Comparison—cont'd

Meter Type	Accuracy	Flow (t/h)	Flow Type	Maintenance	Feature
Impact	+1% AR	0.2–900	Gravity	Good	• Easy calibration • Dust-tight • For horizontal detection no effect due to build up • Change in bulk density can deteriorate accuracy
Coriolis	±0.5% AR −1% AR	4–600	Gravity	Moderate	• Wear due to abrasive material • High-power motor • Not suitable for large-sized material
Microwave	5% AR	0.1–20	Gravity/ pneumatic	Good	• Low cost • Easy calibration
Force flow	±0.5% AR −1% AR	2–500	Gravity	High	• Requires precise alignment
Capacitance	3% AR −5% AR	20–50	Gravity/ pneumatic	Moderate	• Easy installation and calibration • Only a few manufacturers

1.4.0 Solid Flow Measurement System Selection

Like fluid flow measurements, in the case of solid flow measurements also it is of the utmost important to choose the right flow-measuring device based on the application, as well as a few other conditions prevalent for the plant as well as for a particular application. The cost factor and economy cannot be ignored. In this connection it is better to share an experience: the use of an impact scale or Coriolis meter is not uncommon for the measurement of kiln feed as the author has experienced in many places. However, on account of plant configuration it was not possible to used the same in the Jordanian cement Factory Rashadiya. There it was done by a loss-in-weight method with little modification in controls. Thus, what is important is that some constraints from the plant layout configuration as well as material use cause selection changes. In this connection section 4.5.0, and Table I/4.5.0-2 of chapter I may be referenced.

1.4.1 INACCURACY IN MEASUREMENT AND CAUSES

Some of the common issues related to inaccuracy in measurement and thereby plant performance may come from the following issues:

1. Improper selection of flow-measuring device;
2. Installation difficulties and space constraints (feeding equipment);
3. Assumptions on certain variables affecting flow measurement (material characteristics);
4. Equipment mechanical wear and tear—maintenance;
5. Product build ups and associated inaccuracies.

We now very briefly discuss the choices available.

1.4.2 DISCUSSIONS ON SOLID FLOW MEASUREMENT SYSTEM CHOICES

From discussions in Section 3.2.0 it is quite clear that there are a number of solid flow measurement choices. Naturally all of these have

some pros and cons and one may be suitable for a particular application and may not be suitable for another. Therefore, the selection of the right flow-measuring system is really a multidiscipline job. This because one needs to keep in mind the material characteristics, associated parameters, and their variations with plant operation. Obviously all these pieces of information will come from the process engineer. Similarly, during design, the layout is an important characteristic, so mechanical engineers in consultation with process and operation people decide on the feeding device and the instrument engineer needs to select a measuring system which goes well with the material as well as feeding equipment, i.e., if a Coriolis meter is chosen for measurement of large-size coal or limestone it would be disastrous. The flow meter selection mainly depends on the flow measurement application, including the accuracy requirement and overall cost (not only capital cost but also cost related to installation, maintenance, etc.). When material flow measurement is related to pneumatically conveyed material, nonintrusive devices, such as nucleonic measurement microwave Doppler effect measurements, could be in the list of choices, e.g., gamma ray application in the measurement of feed to a precalcinator in a cement plant. Nonintrusive measurements make them more versatile but under certain situations these may not be suitable. Also, loss-in-weight method, enclosed centripetal flow meters are also good choices. For filling of trucks and silos, flow meters like Coriolis/centripetal are good choices. As such, Coriolis is a good choice, but as this is a mechanical instrument with moving parts it is prone to maintenance. The centripetal flow meter has the highest accuracy amongst the flow meters and has no moving parts. For larger batches or continuous processes, belt scale/belt weighers or weigh belts can be used as they do not experience measurement blind spots [10]. However, a few factors, like belt tension, normal wear, and feeding arrangements are important. Therefore, they require frequent calibration. For pulverized coal flow measurement, gravimetric feeder and Coriolis flow meters are good choices. As these are mechanical instruments, these instruments may require frequent replacement of parts or repairs and so maintenance costs can be high. Installation requirements are important issues in the selection of solid flow measurements. Therefore, while making flow measurement selection these issues must be looked into. Along with all these, cost plays an important role. As mentioned earlier, here cost refers to total cost. From capital cost a meter may be cheap but on maintenance costs may be high and make the overall cost of the system high.

1.4.3 FEEDING EQUIPMENT AND INSTALLATION ISSUE

On account of the feeding equipment, at times it is not possible to select the solid flow measurement of choice. Space available may be inadequate for the footprint of the solid flow measurement of choice, and in modern plants space is scarce. The footprint is not the only constraint because a meter with a small footprint may require several feet of additional drop into them in order to produce accurate flow measurement. Finding the space to retrofit a flow meter into an existing process can be a cumbersome ordeal [10].

1.4.4 MATERIAL CHARACTERISTIC AND CONSTANT PARAMETER ASSUMPTION

In many cases it is assumed that many variables, such as density, product size, or even product temperature are constant. In practical cases this may not be so, e.g., coal/limestone bulk density, etc. may vary with different batches. This means all the variables assumed constant are rarely so, e.g., plastic pellets or rice. Moisture content, ambient temperature, change in process and operation may be responsible for changes in these variables, which were assumed to be constant during selection. This means that, while selecting a measuring system, some variations in parameter to a certain extent should be considered. *Some processes may require a "warming up" and/or*

"cooling down" period where the equipment within the process will behave differently (resulting in different "grades" of product) during different phases of production [10].

(For further discussions on two-phase flow [gas-solid flow], which is the case for pneumatic conveying of solids, see Section 1.2.0 of Chapter IX.)

1.4.5 MECHANICAL WEAR OUT

Mechanical type flow measurements are subjected to wear and tear and require extensive maintenance. Therefore, during the selection process, this should be taken into consideration.

1.4.6 MATERIAL BUILD UP

Material build up may cause inaccuracy in measurements. Therefore, right from the start this must be taken into consideration. If not addressed, product build up on the measuring device may cause a variety of difficulties for flow measurement and maintaining accuracy of measurement. This is more so when dealing with powdery materials and sticky materials, such as flours and gypsum. Build up first affects the zero setting and hence zero stability is damaged and calibration may also be out. Thus inaccuracy may creep in.

With this basic discussion presented above and with prior knowledge on the principles of operation of solid flow meters in Section 3.2.0 in Chapter I, it is time to look into details of the various solid flow meter types normally deployed in industrial applications.

2.0.0 MECHANICAL FLOW METERS

Monitoring solids flow poses complexities that are different from the complexities faced with fluid flow. The complexities associated with solid flow metering are related to material characteristics and equipment that have already been discussed in a previous sections (1.4.3 and 1.4.4) of this chapter. In order to achieve optimum plant performance it is essential that flow meters best suited for the application are selected. In this section discussions on various mechanical flow meters normally deployed in solid flow measurement are covered. The discussion starts with deflection chute/centripetal flow meter.

2.1.0 Centripetal Solid Flow Meter

This discussion starts with some recapping of principles of operation in Subsection 3.2.1.1 of Chapter I with detailed explanation.

2.1.1 THEORY OF OPERATION

There is a great deal of similarity between this meter and the impact flow meter; only the measuring force is different. Here the measuring force is inward centripetal force, which is a reaction force generated for centrifugal force. As per Newton's first law of motion, due to the natural motion of an object it continues to move at a constant speed in a straight line and an external force is necessary to depart the object from this type of motion. In this solid flow meter, material is guided through a curved sensing plate. When an object moves in a circular path, there will be acceleration towards the center of the circle along a radius. This radial acceleration, called centripetal acceleration, and is given by mv^2/R, where v represents linear or tangential velocity in a circular path of radius (R). So for mass m, according to Newton's second law, there will be force mv^2/R. This force is referred to as outward centrifugal force. As per Newton's third law there will be an inward centripetal force as a reaction force. In this flow meter material is guided through a curved sensing plate connected to measure this centripetal force by a load sensing system consisting of one or more load cells.

In this case, materials slide across the measuring pan so it cannot measure the impact of particles because they never impact it. Therefore, measurement is based on centripetal reaction not impact. There will be a friction force also, as shown in Fig. VIII/2.1.0-1. Based on the meter design for force measurement, it is possible to identify and cancel the friction component of the force. With the optimum sensor location and arrangement of the meter, the force corresponds to the centripetal measured, i.e., $F = mv^2/R$. Thus it is seen that there is a linear relationship with the

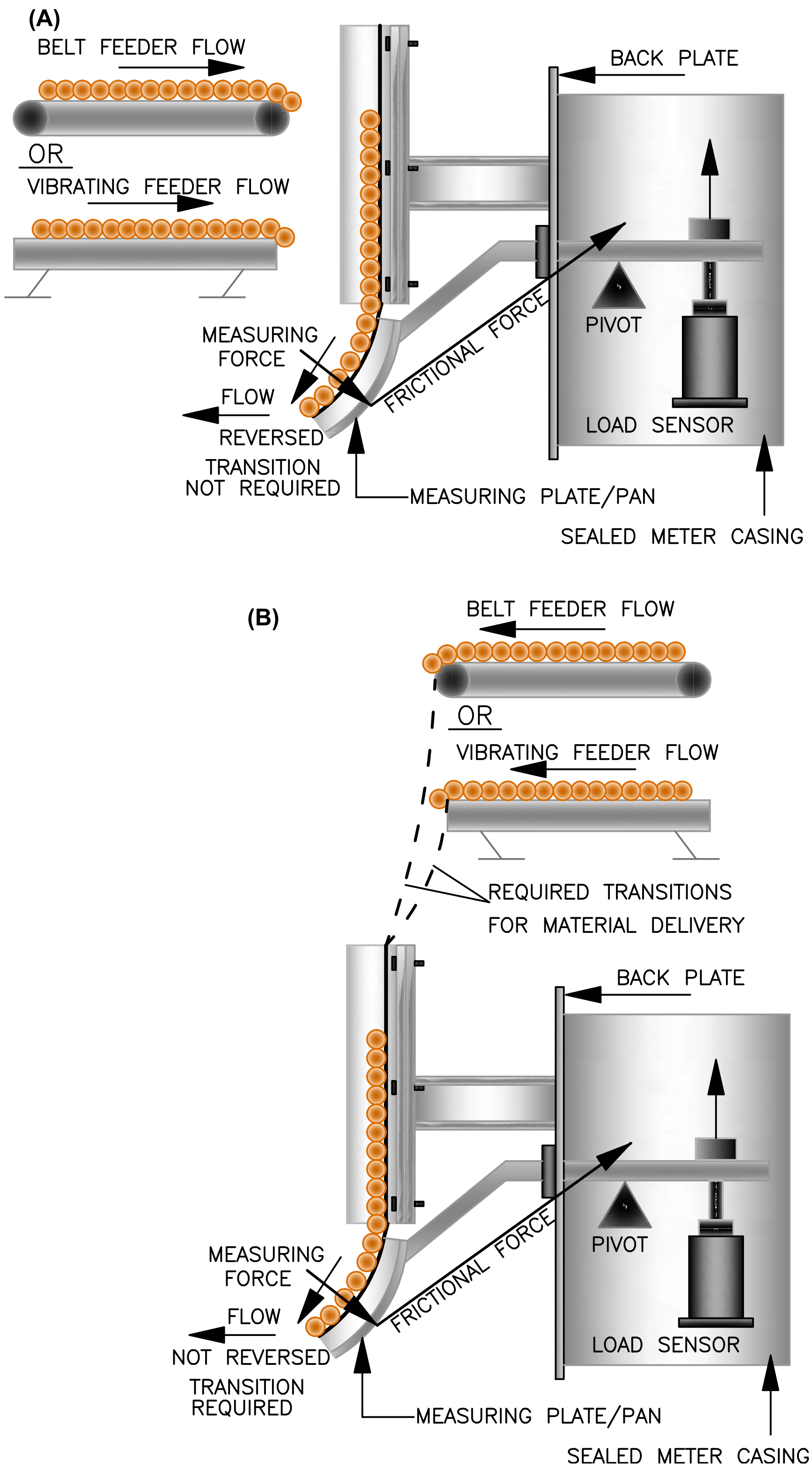


FIGURE VIII/2.1.0-1 Centripetal flow meter details. (A) Centripetal FM with reverse flow installation. (B) Centripetal FM with in-line flow installation.

throughput and this is measured by means of a special friction compensated force sensor.

2.1.2 DESCRIPTIVE DETAILS

A centripetal flow meter is characterized by very high measurement accuracy, e.g., ±0.25% AR. In a process plant, this solid mass flow meter measures bulk solids by directly placing the meter after a number of pieces of feeding equipment. Meters are designed to take the feed from horizontal-direction feeding equipment, such as a belt conveyor or vibrating feeder. Meters are also able to feed from vertical feeding devices such as rotary valves, screw conveyors, and bucket elevators. Therefore, the meters find applications not only in usual process applications but also for preloading controls and dosing tasks in the bulk goods processing industry. Both horizontal as well as vertical footprints are very compact in design, and hence space-saving in many cases, such as in retrofitting applications or offshore applications where space is a real constraint. These meters are robust and made with sturdy aluminum with a stainless steel flow path. For abrasive materials they can be provided with suitable liners. The major parts of the meter are listed here:

- Measuring pass;
- Tangential guide plate;
- Tangential guide plate with liner;
- Back plane structure;
- Support structure;
- Meter casing (with sealing);
- Electronics for signal processing;
- Transmitter to support fieldbus, etc.

Meter accuracy is not greatly affected by changes in product elasticity, density, shape, friction, or even flow fluctuations. The meters are available in an open style that is better suited for the free-flowing nonpowdery nature of bulk solids and for cases where periodic wash downs or frequent access to the product or the meter's flow surfaces are necessary as a part of the process, such as granules, pellets, or even bulky materials, like snack foods or chips. Also, enclosed meters are available for handling free-flowing powdery materials and/or abrasive materials. For hazardous applications these meters are available with a suitable enclosure.

2.1.3 FEATURES AND APPLICATION DETAILS

In this section brief discussions on the features and application details are described.

1. **Features:** The major features of these meters include but are not limited to the following:
   - Robust but compact in design;
   - Reliable and high precision but economical;
   - Friction compensation;
   - No moving parts and so less maintenance;
   - Accuracy independent of bulk density, elasticity;
   - Intelligent sensor arrangement of meter, ensuring zero stability;
   - Suitable enclosures for dust-tight and hazardous applications.
2. **Applications:** There is a wide variety of application areas for this type of meter. Application areas of the meter are detailed in Table VIII/2.1.3-1.

TABLE VIII/2.1.3-1 Applications of Centripetal Flow Meter

Industry	Items	Industry	Items
Construction	Plywood, concrete/roofing products, asphalt, engineering, and recycle material	Food and pet products	Grains, beans, snacks, beverage products, cereal, kibble, feed pellets
Chemical	Industrial powder, mining, glass ceramic, consumer goods	Petrochemical	Rubber/oil extracts, petrochemicals, plastics and additives
Agriculture	Beans, nuts, fertilizers, corn, cornflakes	Energy	Feedstock, ethanol products, coal

2.1.4 SPECIFICATION OF CENTRIPETAL FLOW METERS

Typical specification for a centripetal solid flow meter has been given in Table VIII/2.1.4-1. It is worth noting that as the specification is a general one, all the data will not necessarily match with any particular instrument chosen. Also, it has been attempted to put the best possible data from different manufacturers, and so there will naturally be a deviation from actual instruments. The specification given is just a guide and the reader should specify the requirements for a specific instrument bearing in mind the application in hand.

2.1.5 INSTALLATION

There are various kinds of flanges for the meter to make the connection to the applicable process, including nonstandard connections, such as clamping. The meter can be in either of two orientations, these are reverse flow and in-line flow orientations, as shown in shown in Fig. VIII/2.1.0-1A and B, respectively. It can be seen that in a horizontal feed, for reverse flow (Fig. VIII/2.1.0-1A) the direction of flow is reversed at the meter outlet with respect to feed. In such cases installation is very easy as shown. In contrast, in the case of in-line flow

TABLE VIII/2.1.4-1 Specifications for Centripetal Flow Meter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Solid type	Dry free-flowing granular, powdery, nonpowdery, and various other bulk solids. Usually meant for nonsticky materials. Stubborn and abrasive materials are handled with suitable liner		
2	Feeding style	Both horizontal and vertical feeding		
3	Feeding equipment	Wide variety, belt feeder, vibrating feeder, screw feeder, bucket elevator, rotary valve		
4	Design temperature	Up to 70°C with ambient temperature −20 to 65°C		
5	Typical volume capacity	Wide variation depending on feeding type. Starting from ~1 up to nearly 400 m^3/h		
6	Particle size	Wide variation, typical value: 50 mm		
7	Bulk density	Wide variation possible > 0.35 t/h (performance unaffected by density but min. for operation)		
8	Materials of construction	Aluminum (6061) or stainless steel (SS). SS liner with different coating for guide, SS measuring pan (detachable). Meter body and casing can be SS304/316		
9	Sensing	Basically load cell quantity varies with models and manufacturers		
10	Compensation	Automatic compensation	Friction	
11	Output	4–20 mADC, cumulative pulse frequency and smart version supports: Fieldbus communication (e.g., PROFIBUS/Foundation Fieldbus) available. Capable of supporting Ethernet and other industrial networks, e.g., Devicenet		

Continued

TABLE VIII/2.1.4-1 Specifications for Centripetal Flow Meter—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
12	Output function	Rate flow, totalized flow, alarm, remote reset, zero adjustments		
13	Display and operator function	Digital display, operator reset, calibration, plotting, trending, HMI support, programming		
14	Detachable electronics unit	SS different grades		
15	Enclosure class	IP 68		
16	Power supply	Standard power supply 240 VAC/24 VDC		
17	Hazardous application (refer to author's book*)	ATEX FM load cell and suitable electronics		*[2]
18	*Connection and Mounting Details*			
19	Flow types	For both in-line flow with transition* and reverse flow		*Refer to Fig. VIII/2.1.0-1B
Performance and Other General Details				
20	Accuracy	0.25% AR to 1% AR		(Sensing error 0.017%)
21	Reproducibility	0.1% AR		
22	Turndown	1:20 standard		
23	Field calibration	Remote		
24	Certification	CE and other competent authorities—as per manufacturer		
25	Accessories	Transition and other mounting accessories as required		
26	Special feature	Adjustment of pan angle and others if any		

(Fig. VIII/2.1.0-1B) for horizontal feed, the direction of flow is not reversed but is the same as at the meter outlet with respect to feed. For in-line flow, transitions are installed as shown in the figure.

We now look for another kind of mechanical solid flow meter working on the Coriolis principle.

2.2.0 Coriolis Solid Flow Meter

From Chapter VI, a fairly good idea about the Coriolis force has been gathered. The same Coriolis force is not only utilized in fluid mass flow measurement but is used for measurement of solid mass flow. In this section discussions on Coriolis solid flow meters are given.

2.2.1 THEORY OF OPERATION

The basic theory behind the operation of this meter is that it uses the material's *flow energy through the meter* to create a force popularly known as Coriolis force. This force through the transducer is converted into an electrical signal, which is proportional to the flow rate. The Coriolis force is the force that acts upon a particle accelerating radially outward in a rotating system (frame). This force acts perpendicular to the direction of motion of the particle and is directly proportional to the torque required to accelerate the particle to the circumferential velocity of the rotating system (see Eq. I/3.2.1-4). There are two other forces, frictional force and centrifugal force. These two forces are in different planes and cancel each other out, as depicted in Fig. I/3.2.1-1C. There is a motor located above and outside the flow-measuring enclosure. This motor is connected to a measuring wheel by a shaft to rotate the same at a constant angular velocity. This motor is also connected by a force transmission arm, as shown in Fig. VIII/2.2.0-1, to the load-sensing system (complete with load cell and associated electronics) for determination of instantaneous torque delivered. Material, which is fed from the top of the inlet, flows downward into the top of the measuring wheel. On account of the rotational motion of the measuring chamber by the motor, the materials are diverted outward in a radial direction. Therefore, the guided particles moving vertically are accelerated in a circumferential direction. As indicated earlier, there are three kinds of forces: centrifugal force, Coriolis force, and frictional force. As detailed in Chapter I (Subsection 3.2.1.3 and Fig. I/3.2.1-1C), frictional and centrifugal forces are along the surface of the vane and the Coriolis force is perpendicular to it. Frictional and centrifugal forces not only cancel each other out but at perpendicular, and hence have no effect. Therefore, the measuring principle ensures that frictional forces (between material and measuring wheel or between different material layers) do not affect the flow

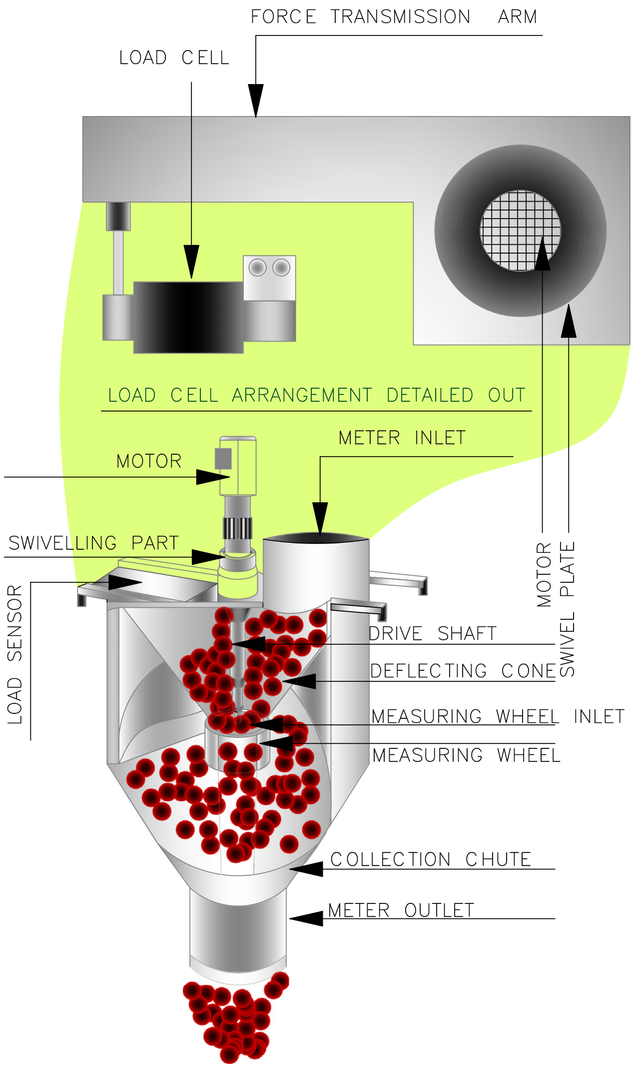


FIGURE VIII/2.2.0-1 Coriolis solid FM details. *This detailing is based on an idea from T.D. Fahlenbock, Coriolis Mass Flow Meter: High Accuracy for High Flowrates, Brabender Technologie; Powder and Bulk Engineering, September 2005.*

measurement and hence there is no question of friction force compensation (as in centripetal flow meters) for this type of flow meter. Also, the physical properties of the material, such as density, friction and impact coefficients, particle size, temperature, and moisture content, do not influence the accuracy or sensitivity of the meter [11]. The repeatability of the meter is also very good. The meter is suitable for both continuous as well as batch operations.

2.2.2 DESCRIPTIVE DETAILS OF CORIOLIS SOLID MASS FLOW METERS

A typical Coriolis solid mass flow meter, consists of a cylindrical housing with an inlet at the top, measuring wheel chamber (with shaft, swivel plate motor), deflecting cone, collection chute, and an outlet at the bottom, below a conical collection chute, as shown in Fig. VIII/2.2.0-1, with important components duly marked therein. At the top of the housing there is one AC motor mounted on a swivel plate through which the driving shaft of the motor extends into the housing. The swivel plate is mounted on flexures that move in one direction in response to force [12]. The drive shaft should be properly sealed to make the system dust-free. At the bottom of the driving shaft is the measuring wheel which is a vaned wheel/chamber. The vanes of the measuring wheel capture the material flow and accelerate the material particles to the rotation velocity. Because the drive motor speed is constant, the flow rate of particles exiting the wheel is constant [12]. The materials coming out of the measuring wheel impact the walls of the conical collection chute and flow downward through the outlet. When there are changes in the flow rate, there is a change in the torque of the motor to accelerate the changed quantity of materials. The changes in torque are transmitted to the load cell mounted on the housing top through a bar-like horizontal extension from the swivel plate, called a force transmission lever to restrict swivel movement. These are separately detailed in Fig VIII/2.2.0-1 (top side). The motor and load cell are controlled through remotely connected electronics. The footprint is moderate—even less than loss-in-weight feeders. When the material mass is accelerated by the measuring wheel's vanes, there will be Coriolis force on the motor. A back torque will be generated by the motor to oppose the Coriolis force. As the motor is firmly mounted on the swivel plate and transmission lever, the motor can counter-rotate only slightly as the flexures bend slightly. Therefore, torque is measured with the help of the load cell connected via a transmission bar. Thus, measured force is directly proportional to the mass flow. At the remote electronics mass flow rate is computed by multiplying mass (which changes motor torque; sensed by load cell) with the velocity of the drive. The uniqueness in the Coriolis flow meter is that the material flow velocity is accelerated in the measuring wheel (running at constant velocity of the motor) so that material exits the flow meter at the measuring wheel's tangential velocity. In other words, the flow velocity is generated by the flow meter itself, making the flow velocity constant. In order to get good accuracy, feeding equipment is extremely important, because this is influenced by material characteristics. Coriolis measuring systems can be successfully applied to almost all kinds of pulverized materials, dusts, and granules such as cement, fly ash, filter dust, lime powders and hydrates, ground slag, silica, and marl, etc.

2.2.3 FEATURES AND APPLICATION DETAILS

In this section, the features and application details of Coriolis flow meters are discussed.

1. **Features:** This is quite a versatile slide flow-measuring instrument, widely used for the measurement of dust and granular materials. However, there are also a few limitations to this meter. For highly abrasive material the meter may not be suitable as the blades may be worn out quickly, calling for quick replacement. Also, large particles may become jammed at the discharge, so another limitation comes from the particle size. Other than these, the meter generally is very good for powdery materials with good accuracy at a high flow rate. Since it is suitable for pneumatic conveying it can withstand pressure up to 10 bar. This flow meter is especially suitable as a high-accuracy flow meter in high flow capacity. Some major features are listed here:
   - Reliable, highly accurate;
   - Insensitive to properties such as density, friction and impact coefficients, particle size, temperature, and moisture content;
   - Good control quality;
   - Economical with low capital and operational costs;
   - Simple for system integration;

- Compact construction;
- Dust-proof housing;
- Immune to external forces;
- Ecologically beneficial;
- Practically emission-free;
- Low power consumption;
- Supports pneumatic feeding.

2. **Applications:** From an application point of view, one can argue that the Coriolis solid flow meter is unique for dust and granular solid materials requiring high precision at a high flow rate. Coriolis solid mass flow meters find their applications in total material flows for batch control and load-out applications. This meter is also suitable for continuous flow measurement with a variety of valves or prefeeders with variable-speed controls. Therefore, the meter can be applied in many plants and can be utilized for the following:
   - Measuring throughput/consumption;
   - Delivery of volume feed rate;
   - Gravity-driven feeding systems;
   - Cement industry, for a variety of pulverized materials;
   - Coal feeding in power plants;
   - Plastic and chemical industries;
   - Pharmaceutical plants.

   It is worth noting that at many places, especially in a cement plant, this meter is gaining popularity. There have been reports that in many places pneumatically conveyed kiln feed measurement by impact scales has been replaced by Coriolis to get rid of the pressure and ventilation differences across the meter and to reduce the sucking effect on the meter.

We now look into the specification of Coriolis solid flow meters.

2.2.4 SPECIFICATION OF CORIOLIS SOLID MASS FLOW METER

A typical specification for a Coriolis solid mass flow meter has been given in Table VIII/2.2.4-1. It is worth noting that as the specification is a general one, all data will not necessarily match with any particular instrument that is chosen. As it has been attempted to pool the best possible data from different manufacturers naturally there will be deviations from actual instruments. The specification given is just a guide and the reader should specify the requirements for a specific instrument bearing in mind the application in hand.

TABLE VIII/2.2.4-1 Specification for Coriolis Solid Mass Flow Meter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Solid type	Dry free-flowing granular, powdery, grain bulk solids. Usually meant for sluggish but nonsticky materials		
2	Feeding equipment	Star feeder, valve, and many other prefeeding systems		
3	Design temperature	Up to 110°C (continuous operation),130°C; ambient temp: −20 to 60°C		
4	Design pressure for pneumatic conveying	10 bar		
5	Typical volume capacity	In various ranges; in terms of feed rate it could be as high as 750 t/h or volume 800 m^3/h available		
6	Particle size	Wide variation, some typical values: powdery to 25−50 mm		

Continued

TABLE VIII/2.2.4-1 Specification for Coriolis Solid Mass Flow Meter—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
7	Bulk density	Wide variation possible >3.8 kg/L (performance unaffected by density but minimum for operation)		
8	Materials of construction	Stainless steel (SS) for components in contact with material. 316 SS measuring wheel meter body and casing coated MS but can be SS304/316 also		
9	Wheel chamber protection	Wear protection and nonsticky coating		
10	Sensing	Basically load cell configuration varies with models and manufacturers		
11	Output	4–20 mADC, cumulative pulse frequency and smart version supports: Fieldbus communication (e.g., PROFIBUS/Foundation Fieldbus) available		
12	Motor power	AC 240/110 VAC 50/60 Hz supply		
13	Output function	Rate flow, totalized flow, alarm, remote reset, zero adjustments		
14	Display and operator function	Digital display, operator reset, calibration, plotting, trending, HMI support, programming		
15	Remote electronics unit	SS different grades		
16	Enclosure class	IP 65		
17	Power supply	Standard power supply 240 VAC/24 VDC		
18	Hazardous application (refer to author's book*)	ATEX FM load cell and suitable electronics possible		*[2]
Performance and Other General Details				
19	Accuracy	0.5% AR to 1% AR		
20	Reproducibility	0.1% AR		
21	Turndown	1:10 standard higher may be possible		
22	Field calibration	Remote		
23	Certification	CE and other competent authorities—as per manufacturer		
24	Accessories	Cooling unit for very hot materials		
25	Special feature	Adjustment of pan angle and others if any		

We now explore another mechanical solid flow meter—the impact solid flow meter which is similar to the centripetal meter, with some differences in sensing and which is quite popular in material handling.

2.3.0 Impact Scale Solid Flow Meter

In this section, the very popular and frequently used impact scale mechanical solid flow meter is discussed. In cement plants this is used in many

applications. The basic principles have already been discussed in Chapter I, Subsection 3.2.1.2. Here more details, including the theory of operation, are described. Prior to beginning the discussions we will have a detailed look at the detailing and types shown in Fig. VIII/2.3.0-1. There are two types of impact scale solid flow meters. In both cases the horizontal component of the impact force is measured when the sensing is carried out, because the vertical component is influenced by gravity (g) making mg force dependent on mass (m)—hence measurement cannot be carried out. The type depends on the *horizontal* component of the force. In one it is sensed by a load cell, whereas in the other it is sensed by a linear variable differential transformer (LVDT). Both types are shown in Fig. VIII/2.3.0-1.

2.3.1 THEORY OF OPERATION FOR IMPACT SCALE SOLID FLOW METERS

As stated at the beginning of this section, there are two types, i.e., load cell and LVDT. Prior to starting the discussions it is important to have a short overlook on the mechanics involved.

1. **Basic mechanics:** In order to understand the mechanics we first refer to the free body diagram shown in Fig. VIII/2.3.1-1. The material falls on the sensing plate from a vertical distance h. Immediately upon striking the materials will be slightly deflected and then slide along the plate. Naturally, as the material slides there will be friction along the length of the plate in the same direction as F_2. Therefore, let us try to compute the horizontal components of various forces. We know that any force can be resolved in 90 degree components. Thus, if we resolve the impact force F_0 one will get F_1 force along the impact plate and another force at right angles to the plate F_2. As stated earlier, there will be another force due to friction (F_f) which will be along the impact plate. As shown in Fig. VIII/2.3.1-1 one can get the net horizontal force (in this case from left to right)

$$F_H = F_{1H} - (F_{2H} + F_{fH}) \qquad \text{(VIII/2.3.1-1)}$$

Here F_{fH} is the horizontal component of frictional force. If l is the length of slide of material and μ is the coefficient of friction then

$$F_{fH} = q_m \cdot \frac{l\mu}{v} \cos\theta \qquad \text{(VIII/2.3.1-2)}$$

when θ is the angle at which the plate is inclined with respect to a horizontal line. For Eq. (VIII/2.3.1-2) it has been assumed that the mass flow rate of the number of particles is q_m, and for derivation of the equation any standard book on particle mechanics can be consulted.

From a basic impact formula, the right angle force *component* applied on the plate can be expressed as

$$F_1 = \frac{q_m}{g} \cdot u_1 \left(1 + \frac{v_1}{u_1}\right) \cos\theta = \frac{q_m}{g} \cdot u_1 (1 + e) \cos\theta \qquad \text{(VIII/2.3.1-3)}$$

where u_1 = velocity of impact, v_1 = resultant velocity at sensing plate, and $e = \frac{v_1}{u_1}$; the coefficient of restitution. Now, taking air friction into account and $0 < k < 1$ one can get

$$u_1 = k\sqrt{2gh} \text{ (using energy equation)} \qquad \text{(VIII/2.3.1-4)}$$

So, putting the value in Eq. (VIII/2.3.1-3) one gets

$$F_1 = k(1 + e) \cdot q_m \cdot \sqrt{\frac{2h}{g}} \cos\theta \qquad \text{(VIII/2.3.1-5)}$$

or

$$F_{1H} = k(1 + e) \cdot q_m \cdot \sqrt{\frac{2h}{g}} \cos\theta \cdot \sin\theta \qquad \text{(VIII/2.3.1-6)}$$

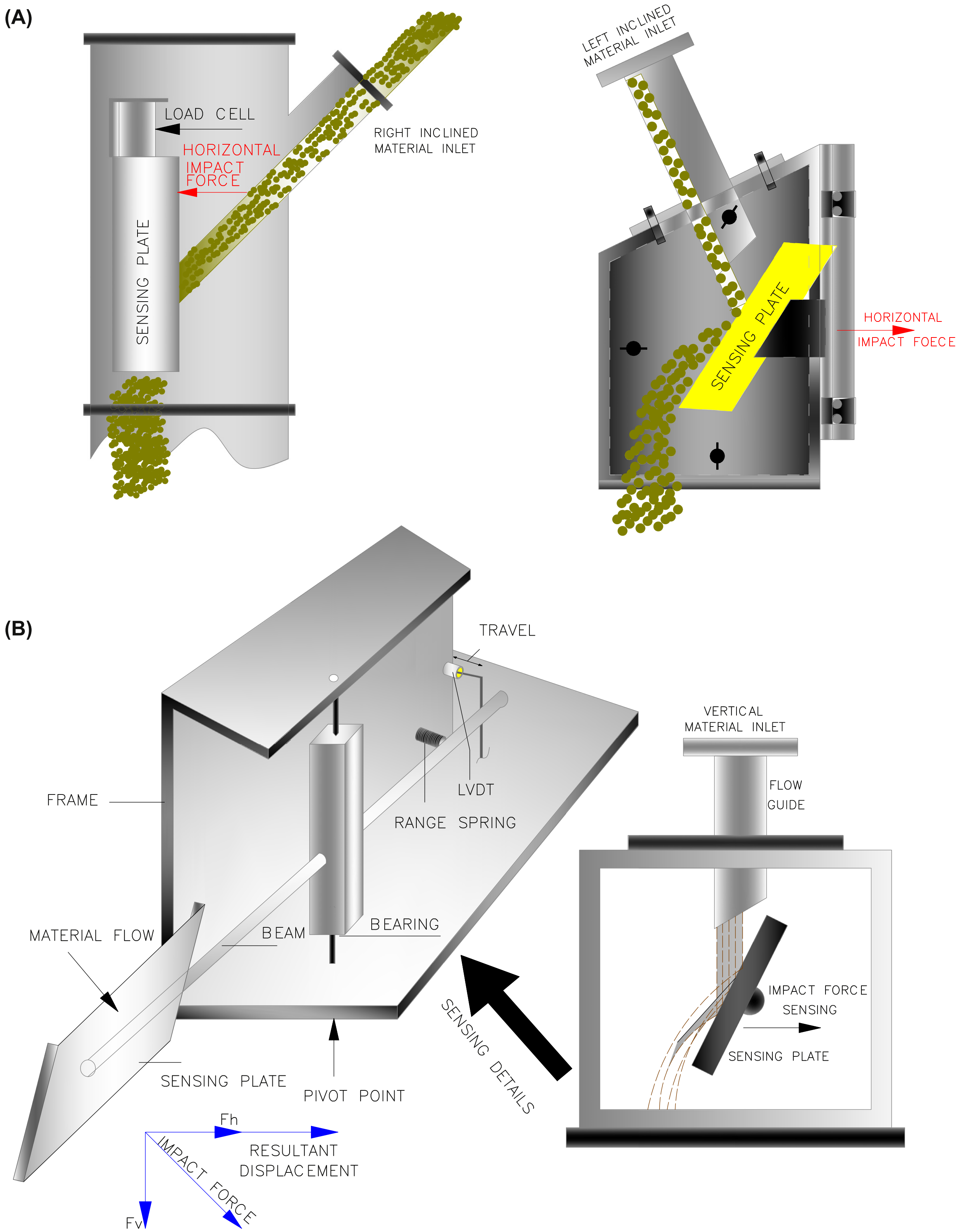
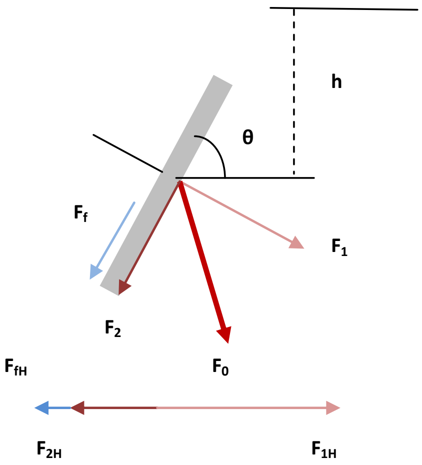


FIGURE VIII/2.3.0-1 Impact scale details. (A) Load cell impact scale. (B) LVDT impact. *(B) Developed based on an idea from Siemens.*



Apparently the difference between F_{1H} and F_{2H} should give the net horizontal force, but there will be another component in the horizontal direction i.e. frictional force between plate and the material along the direction of F_2. So, $F_H = F_{1H} - (F_{2H} + F_{fH})$ when F_f is the frictional force. If mass flow rate is q_m, then $F_{fH} = q_m . \frac{l\mu}{v} \cos\theta$; where l is the distance materials move over the plate, v is the average velocity of material and μ is the coefficient of friction.

FIGURE VIII/2.3.1-1 Horizontal force calculation basis.

Similarly, the parallel component of the force will be

$$F_2 = q_m \cdot k\left(1 - \frac{v_2}{u_2}\right)\sqrt{\frac{2h}{g}} \cdot \sin\theta \quad \text{(VIII/2.3.1-7)}$$

So,

$$\begin{aligned} F_{2H} &= F_2 \cos\theta \\ &= q_m \cdot k\left(1 - \frac{v_2}{u_2}\right)\sqrt{\frac{2h}{g}} \cdot \sin\theta \cdot \cos\theta \end{aligned}$$

$$\text{(VIII/2.3.1-8)}$$

So, putting these values into Eq. (VIII/2.3.1-1) one gets the expression of horizontal force in terms of q_m and so measuring the horizontal force one can account for the mass flow. In these equations $\frac{v_2}{u_2}$ etc. ratios are replaced by A, B which are calibration constants for the meter. The advantage of this impact technology is that the drift due to the mechanical stability of the assembly is eliminated [13]. Materials flow down the intake pipe, which can be vertical or inclined to the left or right side as shown in Fig. VIII/2.3.0-1, and strike the impact plate. The horizontal component of the force is measured and integrated over a specified time to get the rate of flow over time.

2. **Load cell:** In the case of a load cell the horizontal component of the impact force is measured by suspended load cells. Sensing by load cells is a cost-effective solution for impact-based flow meters. The load cell arrangement is shown in Fig. VIII/2.3.0-1A. On account of the impact force on the sensing plate, the bar connected to the plate transfers the horizontal component to the load cell combination. Load cell combinations convert the impact force into an electrical signal and are integrated over time in remote electronics.
3. **LVDT:** An LVDT arrangement is shown in Fig. VIII/2.3.0-1B. There is one beam behind the sensing plate. This beam is also connected with the core of the LVDT and range spring

for restoration, at the other end of the pivot. Here, on account of the impact force on the sensing plate, the connected beam will be displaced. As the beam is pivoted, it will cause the displacement of the core of LVDT to cause an electrical output to the LVDT which converts the impact force into an electrical signal. In a similar manner as described above, remote electronics convert this into an electrical signal proportional to the solid flow rate.

2.3.2 DESCRIPTIVE DETAILS OF IMPACT FLOW METERS

Impact scale load cells may be used in triple beam parallelogram strain gage style as in Siemens SITRANS WF200 or they can be in two single-point load cells as in the Flo way solid impact flow meter. On the other hand, in the case of LVDT sensing, the horizontal impact created by the impact force of the product is sensed by the LDVT. Here the frictionless pivot plays a key role in excluding the vertical force. There is a damper with high viscous fluid to offer mechanical damping for pulsating flow, e.g., SITRANS WF300. These meters do not have moving parts and offer good accuracy. Normally these flow meters are provided with an access door.

1. **Components:** Impact scale solids flow meters are mainly comprised of the following:
   - Varied sizes and styles of inlet guide, some with a lining;
   - Mild/stainless steel (304/316) housing with epoxy painting in some cases;
   - Impact plate of stainless steel;
   - Load cell external/in house with aluminum/SS housing;
   - Integrated electronic box.

   There are also options available for remote electronics mounting. Of the two options for impact scale flow meters, flow meters with LVDT normally can handle high-temperature materials, e.g., 230°C; that with a load cell is integrated with the meter rather closely and usually can withstand material temperatures around 60°C. However, externally mounted load cell designs are also available and these can withstand higher material temperatures up to 100°C.
2. **Prefeeding:** The impact scale is capable of handling aerated flow from an aerated gravity conveyor or air slides. Normally an impact scale can be fed from a numbers of feeding systems such as the following:
   - Belt conveyor;
   - Drag conveyor;
   - Screw feeder short pitched/double flight (fixed/variable speed);
   - Gravity feeder;
   - Bucket elevator;
   - Rotary feeder/valve (fixed/variable speed);
   - Air slide (adapter as applicable)/aerated gravity conveyor;
   - Long and short chute.

   For better results, the height, speed of fall, and angle of impact are important. There are some material characteristics which not only affect the measurement but also affect the life span of the meter.
3. **Material characteristics:** Material characteristics are important for impact scale damages and measurement errors may be caused on account of abrasion, causticity, and adhesiveness.
   - *Abrasion:* Abrasive materials reduce the life of the sensing plate. Not only material properties can cause abrasion, a change in direction can also cause abrasion. It is therefore recommended to use an antiabrasive coating in the sensing plate and inlet guide. PTFE, tungsten carbide, and alumina ceramic coatings are commonly used for highly abrasive materials such as alumina. Polyurethane as an antiabrasive material may not be suitable because it is resilient in nature to absorb some energy. Another way to arrest abrasion is to reduce the speed of material fall, e.g., by using a dead box in the inlet guide.
   - *Causticity:* The causticity of materials can damage the sensor, either directly or due to its vapor. Therefore, sensors should be encapsulated and SS should be used as material sensors like strain gages are kept in gels (e.g., Siemens impact scale). Normally material build up does not affect the results of measurement.
   - *Adhesiveness:* Adhesion of materials on the nonimpact surface of an impact scale is of

some concern as it can affect the movement of the sensing plate. It is important to ensure that the meter is properly leveled to avoid zero drift. It is important to ensure that the materials do not stick on the sensing plate and give rise to build up. Any build up in the sensing plate or inlet guide may cause calibration shift in long run. As the vertical component is ignored, static build up barely affects performance. Depending on the requirements of the sensing plate, inlet guides are sometimes lined with nonsticky materials, such as PTFE. There are certain materials like salt cake and potato flakes which are not at all suitable for an impact meter. It is recommended that the manufacturer's list of items that are not recommended for the meter should be consulted for special applications.

4. **Air flow:** At times it is necessary to have an air flow in the system, for example, for dust collection, in which case it should be both at the inlet and outlet. Light constant low air flow in the meter may vary and can be adjusted in the meter electronics. When it becomes unpredictable it is of great concern. It is recommended to select a suitable place prior to installation to avoid such situations. When there is the possibility of higher measurement inaccuracies due to air flow then it can be reduced by connecting the air flow line between the inlet to the outlet to form a bypass.

2.3.3 FEATURES AND APPLICATIONS OF IMPACT FLOW METERS

Impact scale solid flow meters are one of the oldest solid flow meters, with a proven technology. A few features and application areas of these are enumerated in this section.

1. **Features:** The following are a few features of impact scale solid flow meters:
   - Impact scales can handle the flow of solids from puffed rice/wheat to iron ores of various sizes;
   - Impact scales are normally provided with an easy-access door for inspection;
   - Possibility for dust control with connection to dust filters;
   - Possible for air bypass as already discussed;
   - Impact scale solid flow meters can measure the flow of a low range up to high range of 900 tons/h;
   - As the vertical force component is discarded, material build up barely affects performance, i.e., accuracy;
   - Heavy-duty impact plate, SS external load cell/LVDT makes it suitable for high-temperature material handling;
   - Dust-proof enclosures make impact scales suitable for hazardous areas also;
   - Inlet guide and plates with a lining make it suitable for handling abrasive materials;
   - No moving parts and not prone to maintenance;
   - No frequent calibration is necessary for properly selected meters;
   - Impact scale can be used with a number of prefeeders, including air slides with an adapter.
2. **Application:** As impact scale solid flow meters are generally unaffected by abrasive, corrosive, adhesive (with proper measures), and hot materials they can cater to the measurement of practically any dry bulk solids. The impact scale has very wide applications in almost all industries. Some of the application areas are listed here:
   - Cement;
   - Coke/coal;
   - Wood chips;
   - Pulverized solids;
   - Cereal;
   - Grain;
   - Starch/sugar;
   - Rice/soybean hull;
   - Potato flakes;
   - Plastic pallets;
   - Some pet foods.

As far as fluidity is concerned it can take care of many materials from fly ash to slow-moving leather turnings. Also, these meters, along with the associated electronics, find usage in continuous flow rate measurement, totalizer applications, PID controls, batch controls, blending operations, etc. In the cement industry especially impact flow meters find wide applications from kiln feed to separator returns.

2.3.4 SPECIFICATIONS OF IMPACT SCALE SOLID MASS FLOW METERS

Specifications for an impact scale solid mass flow meter are given in Table VIII/2.3.4-1. It is worth noting that as the specification is a general one, all the data will not necessarily match with any particular instrument chosen. Also, it has been attempted to put the best possible data from different manufacturers, and so there will

TABLE VIII/2.3.4-1 Specifications for Impact Scale Solid Mass Flow Meter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Solid type	Dry free-flowing granular, powdery, grain bulk solids. Food grains, animal feed, plastics, cement, and mineral processing solid aggregates to name a few. Generally nonsticky		
2	Feeding equipment	Wide varieties of feeders, gate valves, rotary valve, gravity flow, and air slide with adapter. Refer to Subsection 2.3.2.2		
3	Design pressure	Less than 1 bar normally		
4	Design/ambient temperature	Design: (−)20−230°C based on type of sensing type and sensor location. Ambient: −20 to −65°C		
5	Typical volume capacity	In various ranges; in terms of feed rate it could be as high as 900 t/h or volume 650 m^3/h available. Tonnage capacity is function of bulk density		As per manufacturer standard
6	Particle size	Wide variation, some typical value: powdery to maximum 15 mm (<30 mm individual)		
7	Bulk density	Wide variation possible, from 0.35 t/m^3 to 3.8 kg/L approximately		
8	Materials of construction	Sensor: load cell Aluminum/SS 316/304 Sensing plate: SS (30/316) Inlet guide: SS 304/316/MS Housing: Mild steel with epoxy painting/SS		
9	Lining (as applicable)	PTFE/polyurethane/alumina ceramic		
10	Inlet guide shape and size	Generally round or rectangle with sizes varying from 50 to 250 mm diameter for circular and up to 300 mm × 500 mm for rectangular		
11	Sensing	Either dual/triple load cell (50/100 lb) (mounting internal/external) or external LVDT with connecting beam		

Continued

TABLE VIII/2.3.4-1 Specifications for Impact Scale Solid Mass Flow Meter—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
12	Output	4–20 mADC, cumulative pulse frequency and smart version supports: Fieldbus communication (e.g., PROFIBUS/Foundation Fieldbus) available		
13	Output function	Rate flow, totalized flow, alarm, remote reset, zero adjustments, control function in continuous process; batching and blending functions		
14	Display and operator function	Digital display, operator reset, calibration, HMI support, control and programming		
15	Remote electronics unit	Aluminum/SS different grades		
16	Enclosure class	IP 65		
17	Power supply	Standard power supply 240 VAC/24 VDC		
18	Hazardous application (refer to author's book*)	ATEX FM load cell and suitable electronics possible		*[2]
Performance and Other General Details				
19	Accuracy	Overall 1% AR 0.5% AR to 1% AR (sensor nonlinearity and repeatability <0.02% AR)		
20	Reproducibility	0.2% AR		
21	Turndown	5:1 to 10:1		
22	Field calibration	Remote		
23	Certification	CE and others competent authorities—as per manufacturer		
24	Accessories	For LVDT damping unit		
25	Special feature	Others if any		

naturally be a deviation from actual instruments. The specification given is just a guide and the reader should specify the requirements for a specific instrument bearing in mind the application in hand.

We now briefly discuss the installation and calibration process for the meter.

2.3.5 INSTALLATION AND CALIBRATION DISCUSSIONS FOR IMPACT SCALES

1. **Installation:** The following are a few basic steps for installation of the meter:
   - Normally flow meters are supplied with a flanged inlet connection. Suitable support should be provided so that the meter does not hang and is rested in a suitable place. The support can be from the top plate of the flow meter or the bottom flange of the meter.
   - The meter must be in a vertical position NOT horizontal/inclined. The load cell must be vertical. The LVDT with beam arrangement should be as per the manufacturer's standard.
   - Flow guides and gaskets, etc. must be properly placed.
   - The prefeeding arrangement along with the associated pipe must ensure that consistency in flow to the impact plate is ensured.

- While unpacking or putting in place, special care is warranted for dealing with the load cell, which does not tolerate any displacement well (very nominal).
- As per the manufacturer's recommendations, suitable arrangement shades, etc. have to be arranged so that the meter electronics are kept at the correct ambience. This is important for integral electronics units. In the case of a remote unit it should be suitably placed (with ambient conditions as per manufacturer's recommendations) duly connected by cables as per manufacturer's recommendations.
- Proper power supply as per manufacturer's recommendations.

2. **Calibration:** The following are the basic steps for testing and calibration. Detailed method cannot be included here as there are variations between manufacturers.
   - In most cases the meters are supplied calibrated. However, field calibration is also done. After proper installation, calibration of the solids flow meter system is carried out in conjunction with the integrator. The calibration is initially done using a test weight. Material tests are recommended for better results.
   - The test rate is the material flow rate represented by the test weight. Calibration of Test Weight and Test Rate (courtesy **Siemens Milltronics Mill flo**) are detailed below. The test weight normally represents a calibration point of 60%−80% of the design flow rate based on the calibration constant of the manufacturer.
   - Test weight = Design flow rate × Calibration point × Calibration constant (manufacturer data)

$$\text{Test Rate} = \frac{\text{Test Weight}}{\text{Calibration Constant of Manufacturer}}$$

   - Here only the basics are covered as the calibration and adjustments of electronic unit switches, etc. are dependent on the type supplied and hence the specifics vary from system to system depending upon the type of operator interface provided with display electronics. The number and modes of switches provided on the unit vary greatly. Details on the fieldbus connections have been described in Chapter XI.

With this, the discussions on mechanical solid flow meters come to an end and we now investigate the solid flow measurement in Section 3.0.0.

3.0.0 GRAVIMETRIC FEEDER AND LOSS IN WEIGHT

When there is a requirement for precision measurement of bulk material, one would consider the benefits of gravimetric feeding. It seems that there are two major advantages associated with gravimetric feeding. One major advantage is that the gravimetric feeding integrates a high-accuracy measurement system to the process, which ensures that the precise rate of material is distributed to the process consistently. The major considerations here come from the requirements for high dosing/measuring accuracies, e.g., 0.5%−0.25%. When there is possibility of wide variation of bulk density, then gravimetric feeding is advantageous. In the case of volumetric feeding such variations will not be taken into account as the measurement is concerned with volume only, irrespective of variations in bulk density. In contrast, as gravimetric feeding is done based on mass, bulk density variations are automatically taken care of. However, volumetric measurement may be less accurate but simpler to deal with when compared with gravimetric measurement. Thus it seems there are pros and cons to either system. It is therefore better to look at the difference between the two systems before opting for the best choice. In Table VIII/3.0.0-1 the differences between the two are briefly illustrated.

From the above table it is clear that feeding gives better accuracy of dosing and also gives

TABLE VIII/3.0.0-1 Difference Between Volumetric and Gravimetric Feeding [14]

Issues	Volumetric Feeder	Gravimetric Feeder
Open/closed loop	Open loop depending on choked or flooded feed and the feeding is by volume only without any feedback arrangement	Material feeding is by weight in a closed loop, meaning that speed is corrected to maintain controller set weight
Feeding equipment	Belt feeder, screw feeder, rotary vane, or vibratory feeder	Normally belt feeder but could be screw feeder or vibratory feeder
Accuracy	Feeding arrangement depends on consistent and uniform prefeeding, hence any change in bulk density or other parameter can cause variation. So accuracy in the range of 1% AR−5% AR without feedback	Since in this type there is constant feedback, any material changes get corrected immediately, to give an output accuracy in the range of 0.5% AR−1% AR maximum
Maintenance	It is simple maintenance of mechanical equipment regarding the motor	Gravimetric feeders require complex maintenance involving maintenance of mechanical equipment, motor drive controls, and maintenance of electronic control systems
Cost	Less costlier than gravimetric counterpart as it does not involve complex control systems	Much costlier on account of complex controls for electrical drive and electronic control system, e.g., PLC

better product quality, which in the course of time will bring the required return on investment to set off the additional cost. Gravimetric feeding is a generic method of measurement. As per the definition of gravimetric feeding described in Table VIII/3.0.0-1, it transpires that gravimetric feeding should be a closed loop with control over the speed of the equipment feeding/dosing. In view of this, the flow meters discussed in Section 2.0.0 of this chapter or nucleonic/microwave flow meters and belt scale/belt weighers may not be described as gravimetric feeding as in these cases it is not necessary to have speed controls of the feeding equipment. *So, what should they be called?* These flow-measuring systems may be called mass flow-measuring devices. Then *what is gravimetric feeding?* As per the definitions discussed in Table VIII/3.0.0-1, gravimetric feeder loss-in-weight method, belt weigh feeder or screw weigh feeder, etc. can be termed as gravimetric feeding because in these cases, based on the feed set point, the feeding equipment is regulated to maintain the required feed rate. How are gravimetric feeders different from belt weigh feeder? The author finds no functional difference between these two. In the case of gravimetric feeders there have been a number of evolutions through which they have gone. The flow rates of solids on gravimetric feeders were regulated by vertical gates or rotary valves, screws, or other devices to regulate volume control. Nowadays for better and precise feeding/dosing, the belt speed controls or controls of both belt speed and the belt loading are undertaken. In the 1950s, A. J. Stock (1900−86) probably first successfully combined the weighing and control of material flow into a single device, now known as the gravimetric feeder. Gravimetric feeders are used to handle pulverized materials, such as limestone coal, in power plants and cement plants. Gravimetric feeders give very good accuracy and hence could be used in various control systems, such as combustion control in fossil fuel power stations. Another kind of gravity feeding system is

known as loss-in-weight (LIW). Like the gravimetric feeder, LIW also provides quite precise measurement and control. LIW finds many applications in pharmaceutical plants. In this section two types of gravimetric feeding, namely gravity feeder and loss-in-weight methods will be covered. The discussion starts with the gravimetric feeder.

3.1.0 Gravimetric Feeder

As indicated during the initial discussions in this section, from a functional point of view the line of separation between a gravimetric feeder and belt weigh feeder is not very thin but also not too prominent. However, from a usage point of view and structurally some differences can be seen. Gravimetric feeders are mainly used in the cases where there is a requirement for precise controls of materials. Gravimetric feeders are primarily used in feeding of pulverized coal, pet coke, etc. to boilers in fossil fuel power plants, as well as in cement plants. Gravimetric feeders are also used for pulverized limestone for cement plants and flue gas desulfurization plants. Gravimetric feeders are mainly available in:

- belt type gravimetric feeders;
- rotary gravimetric feeders.

Although functionally both deliver solid materials with precise controls, from a construction point of view there are variations as well as working principles that are different. Both systems are discussed in the following sections. The discussions start with the working principles of the gravimetric feeder.

3.1.1 PRINCIPLES OF OPERATION FOR GRAVIMETRIC FEEDERS

The basic theory based on which a gravimetric feeder operates is very simple. If it is possible to weigh a defined section of the feeder and from there the tare weight of the feeder section, one can arrive at the net weight of the material. If the feeder moves, in a unit time the defined section passes over the discharge a certain number of times. Then the number of rotations of the feeder section is measured over the unit time. Weight delivered by the feeder will then be given by the multiplication of the speed (number of rotations in unit time) of the feeder and weight of the defined section net weight. Therefore, in a gravimetric feeder, instantaneous values of the defined or measuring section of the feeder are measured and this is multiplied by the rotational speed of the feeder (in the case of a belt feeder the linear speed, which is proportional to rotational speed, is easily calculated from the rotational speed). Therefore, multiplication of load cell data (used to measure the weight of the measuring section) with the rotational speed of the feeder will compute instantaneous feed data. These feed data, when integrated over a specified unit time, will give the feed rate. Based on the unit time chosen and weight-measuring unit chosen, it can give kg/s, tons/h, lb/s, or lb/h. Basically, the same principle is used for belt weighers/belt scale/belt weighers, etc. As stated above, there are two kinds of gravimetric feeders, namely, belt type gravimetric feeders and rotary gravimetric feeders. We now look into the details of the working principles of both types.

1. **Belt type gravimetric feeder:** This discussion starts with typical belt type gravimetric feeders as depicted in Fig. VIII/3.1.1-1.

   The gravimetric feeder weighs material on a belt between two fixed points, which defines the span or a defined section stated in the initial discussions, precisely located in the feeder body. A roller is located at the midway point of the span. This is supported at each end by a set of load cells. Thus, the gravimetric feeder weighs material on a length of belt between two fixed rollers suspended from load cells (this could be a single cell). It measures half the weight on the span, which varies as the material quantity varies on the belt. The load cells are basically a transducer to generate an electrical signal directly proportional to the weight supported. The microprocessor takes samples of the output of each load cell many

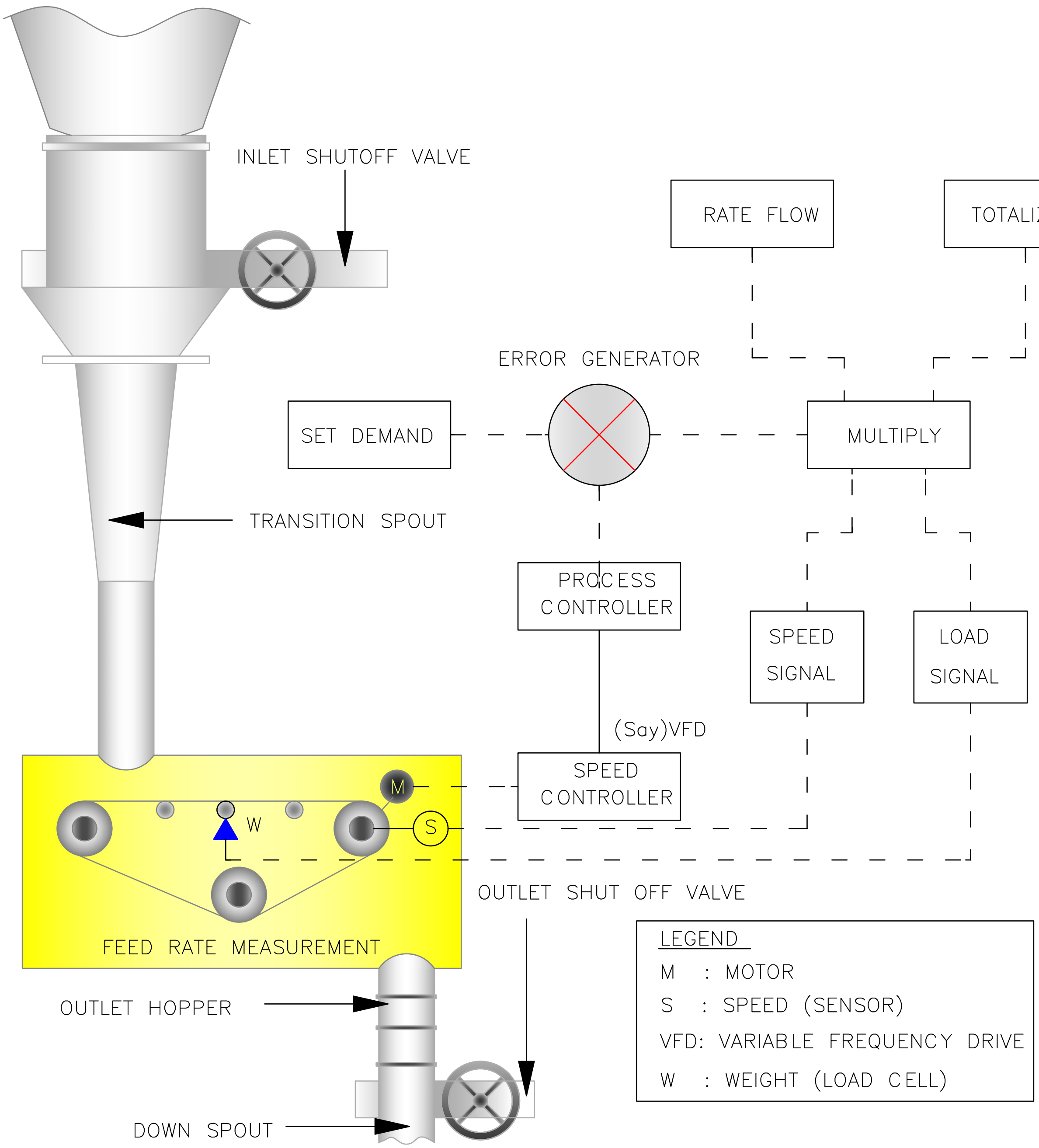


FIGURE VIII/3.1.1-1 Belt gravimetric feeder.

times a second [15]. Similarly, the belt speed is measured by a speed sensor, e.g., a tachometer, mounted on the motor shaft to obtain the proportional speed signal for the belt. The speed sensor is sampled by a microprocessor. Both signals from load cells and speed signals are multiplied by a signal processing unit in the control cabinet of the gravimetric feeder to get an instantaneous feed rate, which when integrated over unit time gives the feed rate in the desired units as described above. An intelligent signal processing unit adjusts and matches the feeder output by adjusting the speed. An accuracy of nearly 0.5% AR is possible.

2. **Rotary gravimetric feeder: (Confession:** *The rotary gravimetric feeder described is based*

on the description from FLSmidth Pfster's patented rotor weigh feeder technology.)

A rotary gravimetric feeder is depicted in Fig. VIII/3.1.1-2 which shows that there exists one weigh measuring axis which plays an important role in weighing. This imaginary line is formed by joining the lines between the two bearings. The rotor body is mounted on these bearings. As can be seen in Fig. VIII/3.1.1-2, this axis is symmetrical with respect to the bearings but eccentric to the rotor shaft, which is symmetric with

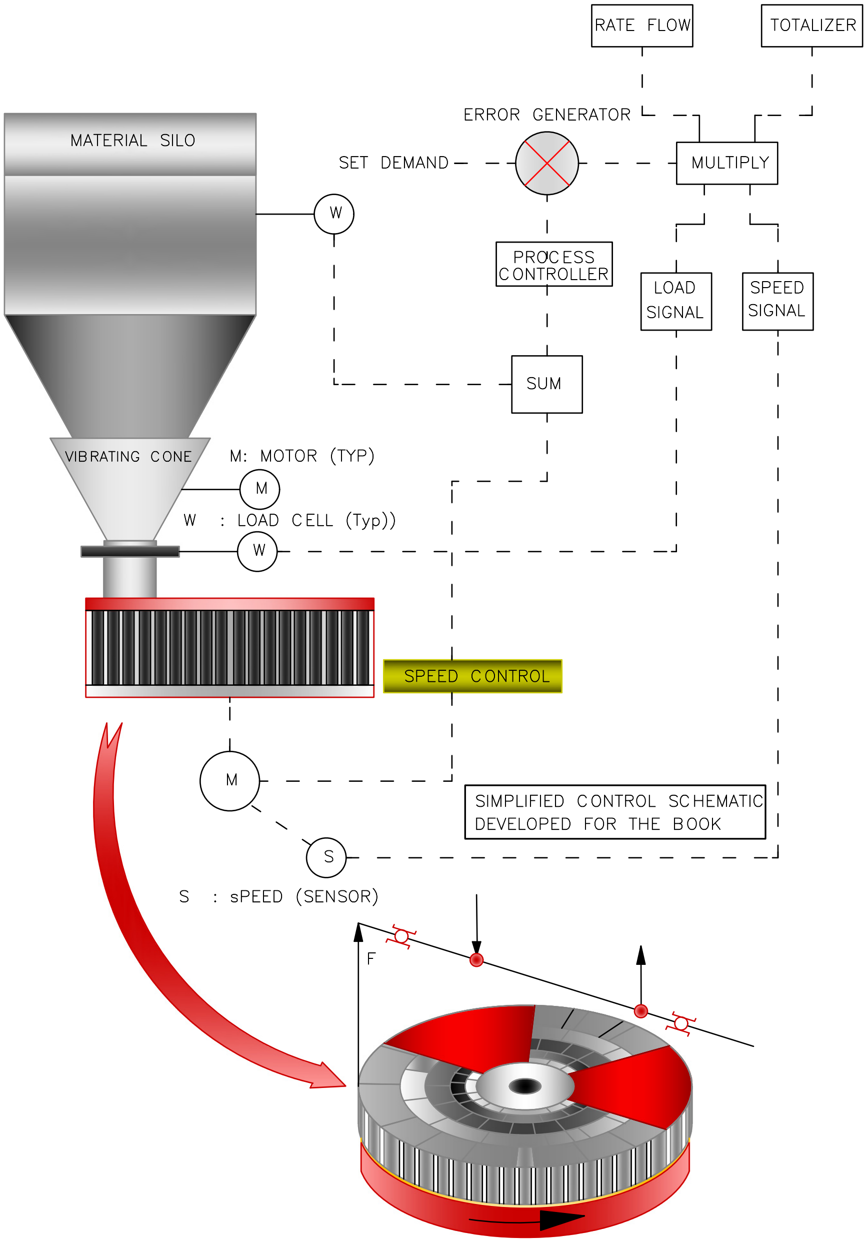


FIGURE VIII/3.1.1-2 Rotary gravity feeder. *Scale developed based on F.L. Smidth, Gravimetric Solutions for Power Industries, Pfister. http://www.flsmidth.com/~/media/Brochures/Brochures%20FLSmidth%20Pfister/Brochures/BrochurePfisterSolutionsPowerIndustry0217.ashx. Courtesy; Developed based on Gravimetric and Volumetric Coal Feed Systems for Boilers, Schenck process (internet document). http://www.schenckprocess.com/applications/Pressurized-Gravimetric-Feeders. Courtesy: F.L. Smidth.*

respect to the rotor wheel. So, in the weighing axis there are two points corresponding to the bearing, and in the axis, there is a third point where there is a suspended load cell to weigh the content in the rotor wheel gravimetrically (F). This means the rotor weigh feeder measures in kilograms and is therefore a real scale. As seen in the detailing, the gravity force F is measured by an algebraic sum of the two forces at the inlet and outlet. Therefore, the gravimetric force (F) provides information on the weight of bulk material in the rotor weigh feeder before material discharge. The material load of the rotor and the related rotor wheel position are stored by the weighing electronics [16]. The control philosophy rotor speed is that when there is less material in the rotor, it will result in a higher angular speed, and with more material the result will be a lower speed. Therefore it is necessary to note the rotor wheel position at the time of discharge. The electronic controller calculates the speed of the motor for the time of the discharge (in conjunction with mass just before discharge from load cell). It uses the set feed rate and the measured bulk material mass to calculate the angular speed of the rotor to get an accurate feed rate. This also compensates for the variations in bulk density. The rotor weigh feeder discharges the material at the outlet with a highly accurate mass stream.

Gravimetric weigh feeders find major applications in delivering coal either in crushed form and/or pulverized form. They are also used in transporting pulverized limestone. In the next section features and applications of gravimetric feeders are briefly discussed.

3.1.2 FEATURES OF GRAVIMETRIC FEEDER WITH DESCRIPTIVE DETAILS

The following are a few features of gravimetric feeders that are worth noting:

1. Suitable for continuous plant weighing or rate control for batching;
2. Gravimetric feeders are capable of handling of both crushed coal/pet coal and pulverized (for rotary gravimetric feeder) coal and limestone;
3. Rotary gravimetric feeders can withstand high pressure and high pressure shock up to 10 bar (rotary type);
4. Integrated pneumatic fuel transport and feeding possible in cement and power plant by rotary gravimetric feeder;
5. Direct-mounted weighing with set of load cell in suspension;
6. Dual-load cell weigh suspension, possibility for continuous comparison/alignment check;
7. No moving parts, for weighing;
8. Possible to maintain exact demand of flow/feed rate irrespective of bulk density (which also affects calorific value directly) change;
9. Efficient in maintaining stoichiometric ratio for combustion control, as direct corollary to this there will be better NO_x control and superheater controls in boiler applications;
10. Less possibility for loss of ignition in boiler applications;
11. With large pulleys, maximum belt wrap is ensured to eliminate slippage for belt gravimetric feeder;
12. Low tension can ensure higher life for bearing for belt gravimetric feeders;
13. In high-pressure applications, as per NFPA85 and NFPA 50 body shell;
14. Easy-access gasketed door to ease maintenance for belt gravimetric feeder, while all components are easily accessible from outside for rotary gravimetric feeder;
15. Rotary gravimetric feeders are self-cleaning with single slow-moving drive;
16. Rotary gravimetric feeder parts are accessible from outside so much easier for maintenance;
17. Some belt gravimetric feeders are provided with dual-speed encoders at tail pulley and motor to detect belt breakage or component failure;
18. With critical component redundancy reliability, high accuracy and safety are assured;

19. Lower overall operating and maintenance cost;
20. Gravimetric feeders in combustion applications ensure improved combustion controls, less slagging, fouling, and corrosion;
21. Gravimetric feeders help to improve performances of pulverizers/cyclones/combustors;
22. Gravimetric feeders are normally provided with automatic cleaning facilities;
23. Gravimetric feeders are available in most cases as self-contained intelligent control systems with powerful processors and peripherals to support an interactive operator interface with intelligent displays and support standard communication systems like fieldbus, e.g., Profibus, foundation fieldbus, blue tooth, PC interface, etc.;
24. Diagnostic features in gravimetric feeders are worth noting;
25. Rotary feeders show greater stability and higher accuracy over long periods of time for a wide range of material;
26. Rotary gravimetric feeders are available in fully enclosed form, suitable for hazardous environments;
27. For rotary gravimetric feeders, a sealed air system is not necessary and also there is no spillage;
28. For rotary gravimetric feeders in-line blending of a number of fuels in one place is possible and up to four feeders below one silo is possible;
29. Rotary gravimetric feeders are full metal constructions without rubber, belt, idler and pulley;
30. Rotary gravimetric feeders can be accommodated within a short distance between the bunker outlet and mill inlet with less downspout length [16].

3.1.3 APPLICATION AREAS OF GRAVIMETRIC FEEDERS

Gravimetric feeders find wide applications in power and cement plants. Rotary gravimetric feeders also find applications in nickel plants and plastic plants.

1. **Belt type gravimetric feeder:** Belt gravimetric feeders are used for carrying crushed materials like coal and raw materials for raw mills in cement plants. In addition to fuel flow measurements, gravimetric feeders can also be used for limestone and other materials in cement and power plants, e.g., limestone (for FGD plants in power applications). The typical applications of belt type gravimetric feeders have been detailed in Fig. VIII/3.1.3-1.

   In Fig. VIII/3.1.3-1, the applications of crushed materials in power plants and cement plants are shown. In power plant applications these feeders can be used to carry crushed coal to pulverizers, or crushed limestone/coal for circulating fluidized bed combustion (CFBC), or even for stoker fired boilers. In power plants, they can be used to measure limestone for FGD, and in cement plants they can be used for measuring feeds to raw mills.
2. **Rotary gravimetric feeder:** In use, rotary gravimetric feeders are more versatile than the belt type gravimetric feeders discussed above, to carry pulverized fuels/raw materials directly to burners and silos of cement plants, respectively. These are used mainly in firing of hot gas generators, calcinators/kilns in cement plants. In all such cases the pulverized materials are transported pneumatically directly to the burners of the boilers in power plants, hot gas generators, precalcinators/kilns in cement plants with the help of blowers, as shown in Fig. VIII/3.1.3-2B. Also, some small power plants now tend to use pneumatically transported fuel to the burners, especially for lignite plants. Since this is available in a suitable enclosure there is less spillage and seal air fans are not required. They are also suitable for use in hazardous applications. It is possible to use a single bin/silo to cater for a number (maximum four) of different pneumatic transportations of pulverized materials, as detailed in Fig. VIII/3.1.3-2, where solid flow measurements by a rotary gravimetric feeder for crushed materials and pulverized materials

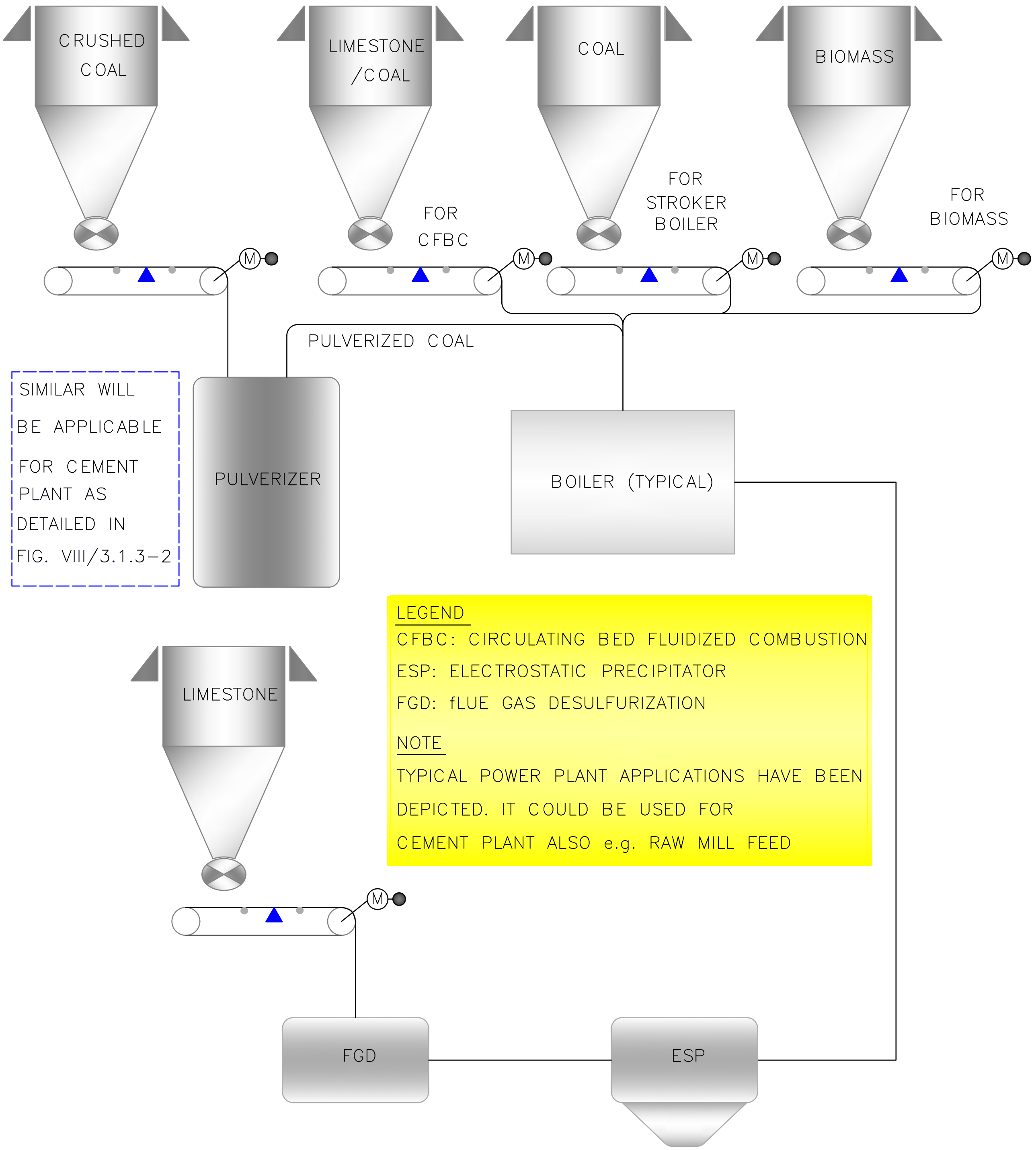


FIGURE VIII/3.1.3-1 Belt type gravimetric feeder applications.

have been depicted. Cement plant applications are shown by a blue dotted line for crushed material measurements. Pulverized material measurements are mainly applicable for cement plants.

3. **Combustion applications (power plant):** In power plants the use of gravimetric feeders in the USA is more popular, however gravimetric feeders now find wide applications in other parts of the world also, e.g., Germany,

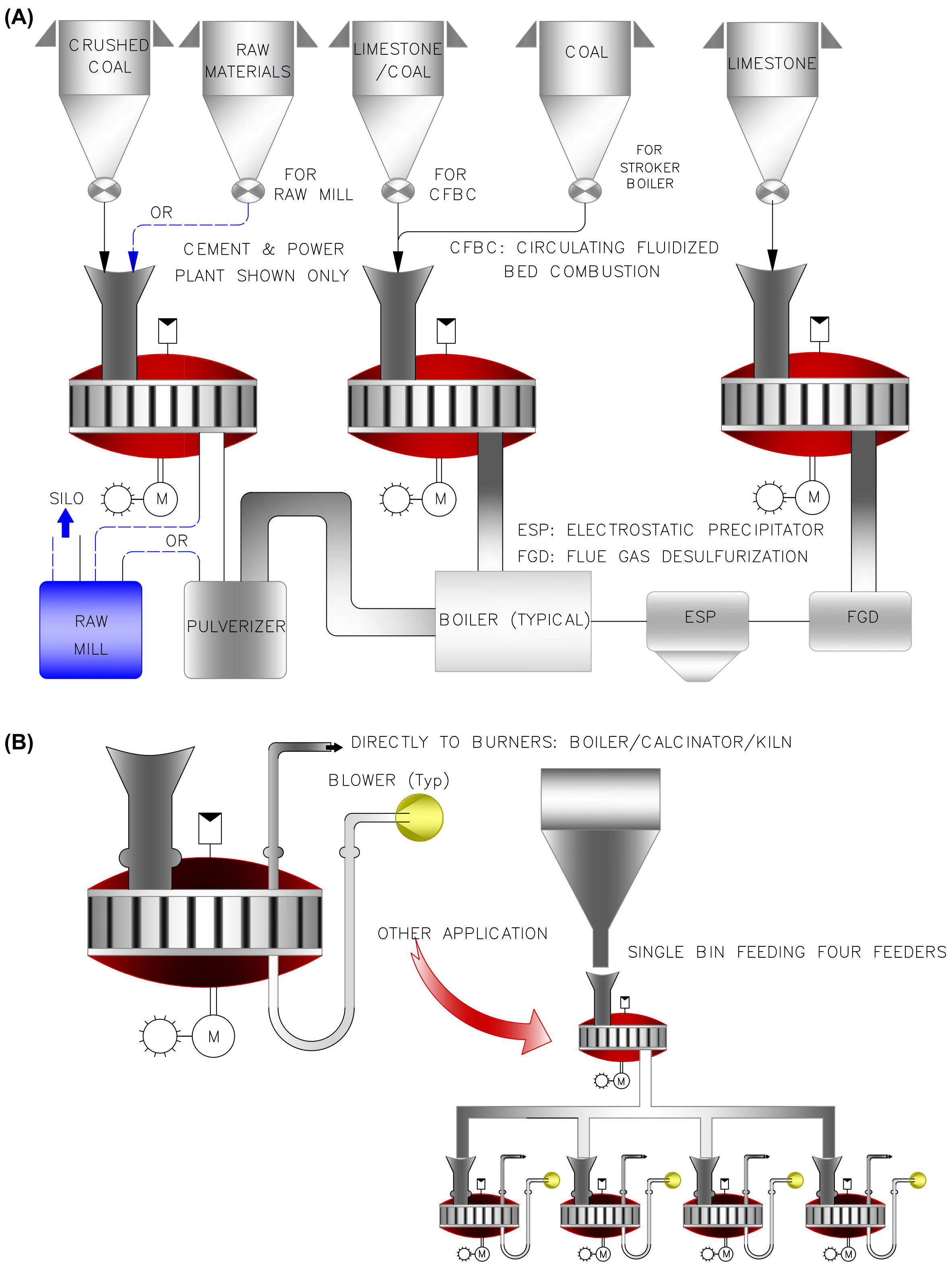


FIGURE VIII/3.1.3-2 Rotary gravimetric feeder applications. (A) Rotary gravimetric feeder for crushed materials. (B) Rotary gravimetric feeder for pulverized materials.

Denmark, and India. In cement plants, the carrying of pulverized fuel to the precalcinator/kiln is common. On the other hand, in fossil fuel power plants, normally pulverized fuels are carried from the coal mill outlet to burners with the help of primary air (PA) fans. One of the reasons for this is that in the case of utility boilers there are a number of burners distributed not only over a wide area but also over different heights unlike single/dual burners for kilns/calcinators. In such cases mill calibration and fuel control can be problematic. However, a few small power plants have been using pulverized fuels from bins, where rotary gravimetric feeders can be applied. For any combustion, especially in power plants, the use of gravimetric feeders is of immense importance. Major issues related to this (mainly for power plants) are listed here:

- *Stoichiometric ratio (λ):* From basic combustion theory it is known that when stoichiometric ratio as defined in Fig. VIII/3.1.3-3, is very near 1, combustion is complete. From a safety point of view it is always advisable to maintain a slightly air-enriched environment, i.e., λ slightly higher than 1. This is achieved by a lag-lead circuit in a combustion control system. When air is higher than the minimum requirement, a safe air-enriched atmosphere will be maintained but heat will be lost with excess air leaving through the chimney. Similarly, if there a fuel-enriched environment is maintained then there will be incomplete combustion and hence less release of heat and a lower possibility of unsafe conditions. When only the feeder speed is considered in a fuel flow control loop in volumetric measurement, then the actual fuel flow may be different from the combustion demand. So, λ may not be maintained near 1. With volume flow measurement the variations in density and hence caloric values are not taken care of. Therefore, combustion cannot be completed; and so there will be a loss in the system. On the other hand, in a gravimetric feeding system, since mass is balanced, the exact quantity of fuel is used to accelerate complete combustion and so λ near 1 can be maintained easily.
- *Avoid loss of fire/ignition loss:* High furnace pressure due to more air and/or a sudden reduction in feeder speed can cause a loss of fire and both such conditions can happen when there is a mismatch between fuel demand and actual fuel quantity measured by the volumetric method. Such situations can be avoided with a gravimetric feeder.
- *Avoid slagging (molten ash):* When fuel flow is measured by gravimetric feeder, then there will be reduced variation in the feed rate, and hence less variance in excess air between the burners. This results in consistent gas temperatures and less slagging of the burner environment.
- *Reduced NO_x:* For NO_x control, less excess air is necessary, which is achieved when a gravimetric feeder is used for fuel flow measurement. For details on NO_x control refer to Ref. [17] by the author.

Stoichiometric ratio (λ): *Stoichiometric ratio refers to the ratio of air and fuel required to produce a chemically complete combustion process. In stoichiometric combustion process the fuel is completely burnt so that carbon, hydrogen and sulfur are completely converted to CO_2, H_2O and SO_2 respectively and λ =1. This is a theoretical value, in reality it is the ratio of air and fuel when CO production is the minimum. In reality this value of λ is very near 1 but higher than 1.*

FIGURE VIII/3.1.3-3 Stoichiometric ratio.

- *Maintenance of superheater temperature at desired set point:* For superheater temperature control it is necessary that changes in excess air should be sensed and variations of excess air will affect superheater temperature control. So, when gravimetric feeders are used there will be less of a variation in excess air, and hence greater stability in superheater temperature control.
- *Feed flow controls:* Feed water control, especially for once-through/supercritical/ultrasupercritical boilers is a function of fuel flow control and superheater temperature control, and so gravimetric fuel flow will always give better results.
- *Fast and stable load change:* Gravimetric feeders always provide high accuracy, and are responsive over the feed rate range. Therefore, the feed rate is instantly and accurately adjustable with load changes. This makes load changes very fast, stable, and more efficient.

Within the limited scope of this book these will be touched upon only; for detailed discussions the readers may go through ***"Power Plant Instrumentation and Control Handbook"*** by Swapan Basu and Ajay Debnath [17], published by: Elsevier BV.

We now us look into specification details of the gravimetric feeder types.

3.1.4 SPECIFICATIONS OF GRAVIMETRIC FEEDERS

The specifications for gravimetric feeders are given in two tables below. Table VIII/3.1.4-1 gives the specification for a belt type gravimetric feeder, whereas the rotary gravimetric feeder specification has been given in Table VIII/3.1.4-2. It is worth noting that as the specification is a general one, all the data will not necessarily match with any particular instrument chosen. Also, it has been attempted to put the best possible data from different manufacturers, and so there will naturally be a deviation from actual instruments. The specification given is just a guide and the reader should specify the requirements for a specific instrument bearing in mind the application in hand.

TABLE VIII/3.1.4-1 Specification for Belt Type Gravimetric Feeder

SL	Specifying Data	Standard/Available Data	User Spec.	Remarks
1	Solid type	Crushed coal/bituminous coal and other crushed materials such as raw mill feed in cement plants		
2	Feeding equipment	Wide varieties of hopper/bin and/or silos with discharge valves		
3	Design pressure	High-pressure versions up to 3.5 bar are available		
4	Design/ambient temperature	Design: Maximum 230°C. Ambient: −20 to 50°C		
5	Typical capacity	0−150 t/h, typical; depends on manufacturer		As per manufacturer standard
6	Inlet size	Normally 600−900 mm diameter		
7	Belt width	Typically 600−1200 mm		
8	Materials of construction	Shell: Carbon steel with suitable hardening Other parts made up of SS		
9	Sensing	Load: Suspended redundant load cell Speed: Tachometer or other speed sensor		

Continued

TABLE VIII/3.1.4-1 Specification for Belt Type Gravimetric Feeder—cont'd

SL	Specifying Data	Standard/Available Data	User Spec.	Remarks
10	Drive	Direct shaft-mounted geared motor		
11	Speed control	Normally variable-frequency drive (VFD)		
12	Output	4–20 mADC, cumulative pulse frequency and smart version supports: Fieldbus communication (e.g., PROFIBUS/Foundation Fieldbus) Some support bluetooth, PC interface, and standard links. Also		
13	Output function	rate flow, totalized flow, alarm, remote reset, zero adjustments, control function in continuous process; batching and blending functions		
14	Display and operator function	Digital display, operator reset, calibration, HMI support, control and programming. Remote intelligent electronics cabinet and local control panel		
15	Electronic cabinet	Remote intelligent electronics cabinet and local control panel. Aluminum/MS different grades		
16	Enclosure class	IP 52		
17	Power supply	Standard power supply 240/110 VAC, 50/60 Hz/24 VDC		
Performance and Other General Details				
18	Accuracy	Overall 0.5% AR		
19	Reproducibility	0.2% AR		
20	Turndown	10:1 to 20:1		
21	Field calibration	Remote panel		
22	Application	Major application areas, including power and cement plants		
23	Special feature	and others if any		

TABLE VIII/3.1.4-2 Specification for Rotary Type Gravimetric Feeder

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Solid type	Crushed coal/bituminous coal and other crushed materials such as raw mill feed in cement plant. Pulverized or ground materials		
2	Feeding equipment	Wide varieties of hopper/bin and/or silos with discharge valves. Extraction from silo is also possible		
3	Design pressure	High-pressure versions up to 10 bar are available		
4	Design/ambient temperature	Design: Maximum 250°C Ambient: −20 to 50°C		

Continued

TABLE VIII/3.1.4-2 Specification for Rotary Type Gravimetric Feeder—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
5	Typical volume capacity	0—200 t/h typical, depends on manufacturer		As per manufacturer standard
6	Down spout	Short length		
7	Materials of construction	All metal construction CS/SS		
8	Sensing	Load: Suspended redundant load cell on measuring axis as shown in Fig. VIII/3.1.1-2; speed: Tachometer or other speed sensor		
9	Drive	Top mounted on rotary feeder		
10	Speed control	Normally variable-frequency drive (VFD)		
11	Output	4—20 mADC, cumulative pulse frequency and smart version supports: Fieldbus communication (e.g., PROFIBUS), CAN communication is also possible. PC interface MODBUS and standard links are available also		
12	Output function	Rate flow, totalized flow, alarm, remote reset, zero adjustments, control function in continuous process; batching and blending functions		
13	Display and operator function	Digital display, operator reset, calibration, HMI support, control and programming. Remote intelligent electronics cabinet and local control panel		
14	Electronic cabinet	Remote intelligent electronics cabinet and local control panel of sheet metal		
15	Power supply	Standard power supply 240/110 VAC, 50/60 Hz/24 VDC		
Performance and Other General Details				
16	Accuracy	Overall 0.5% AR		
17	Reproducibility	0.2% AR		
18	Field calibration	Remote panel		
19	Application	Major application area includes power and cement plant		
20	Special feature	Supports pneumatic conveying; others if any		

3.2.0 Loss-in-Weight Measurement

The loss-in-weight feeding system, which has its history way back in the 1970s, is one of the preferred feeding systems for solid materials. It is also used for liquid services. When there are high variations in material bulk density, volumetric feeding will result in high fluctuations in the feed rate (e.g., fluctuations in the filling of the screws). This fluctuation in feed rate results in inconsistencies in material delivery, and hence variations in end-product quality. This is very important, especially in pharmaceutical industries.

Also, in the case of cohesive materials there may be bridge building or packing in the hopper, and there will be an increased chance of fluctuations in volumetric feeder measurement.

The loss-in-weight feeding method is well-accepted as a precise, reliable, and dependable metering mechanism for versatile dry solids or liquids. This method is not delicate or temperamental, instead it is very robust and suitable for installing in adverse industrial environments. Loss-in-weight measurement operates strictly on the basis of the loss of a specific amount of product (weight) in a specific amount of time. Therefore, there is no other factor involved, and there is no zero reference for feed rate calibration. Also, the loss-in-weight feeding method does not require frequent calibration or adjustment. The loss-in-weight method refers to a kind of feeding arrangement or material dispensing arrangement; normally it refers to the feeder. This arrangement can be used for solid and liquid systems, but usually it refers to solid measurement; hence the term loss-in-weight feeder is deliberately avoided. Basically this is a gravimetric feeding arrangement. This method uses a gravimetric feeding device which receives material from the product hopper in the upstream supply chain and accurately doses/feeds the material to the process at a predetermined and defined feed/dosing rate through a screw feeder (auger/helix), belt, vibrating feeder, and other feeding device. As the name implies, the feeding rate or the operation of the feeding device is regulated by the amount of live load that is lost as the product is discharged. In order to do this the control system of the feeding device receives constant feedback from a sensitive weighing device which ensures that a precise amount of material is delivered continuously or in each batch Therefore, loss-in-weight feeding normally regulates the dispensing of material by weight into a process at a precise rate in a controlled manner based on loss of active load in the upstream hopper.

This discussion starts with the basic principles of operation; for a basic idea Subsection 3.2.2.1 of Chapter I may be referenced.

3.2.1 PRINCIPLES OF OPERATION OF LOSS IN WEIGHT

A loss-in-weight measuring system is not just one instrument or device but consists of a number of devices and pieces of equipment along with a control system. The entire system follows a cyclic process. In this section both principles of operation and procedure are discussed.

1. **Principle:** A loss-in-weight (LIW) feeder/feeding system controls the dispensing of material into a process at a precise rate in a gravimetric manner. The target feed rate is generally known as the loss of *weight set point.* A loss-in-weight feeding method weighs the whole hopper/feeder system, together with the product utilizing the weighing system. In the case of a gravimetric feeder it has been seen that gravimetric solid flow is measured by multiplying the weight of the material added to the feeder for discharge and the speed of operation of the feeder. In the case of the loss-in-weight method, the loss in weight (contrasting with the addition of weight) is monitored. The basic principle behind the loss-in-weight method is to dispense the product at a constant loss of weight (w) per unit time t, such that the material in the hopper is delivered by the feeding system at a constant rate, i.e., $dw/dt = \text{constant}$. When the material is fed through the feeder/feeding system to the process, then there will be a decrease in the weight of the system. The speed of the loss-in-weight feeder/feeding system is regulated to match the feed (discharge) rate to the desired feed rate set point, i.e., the speed of weight loss matches the desired feed rate. The loss-in-weight feeder controls continuously check whether the material is flowing. *All components* (the feeder, the hopper, and the material) *and/or any product* they contain are continuously weighed during operation [18]. LIW systems are used for small to medium-sized feeding systems. At low feed rates, the net weight per unit time is small. Therefore, in all such cases high-resolution weight

systems are necessary. The electronic controller/system continuously samples and monitors the load cell signals for weight, and the tachometer/speed sensor measures the actual motor speed. Monitored signals are duly processed at the controller to generate the necessary output for controlling and optimizing the speed of the feeder/feeding device. Some controllers also compare the totalized quantity of material actually fed over a period of time against the target, and, following calculation, execute incremental corrective changes to the feeder speed to optimize long-term feeder accuracy [19]. For better accuracies, interpolation and extrapolations algorithms are used. Interpolation algorithms are used to estimate the weight data between verified measurements, whereas the extrapolation method is used to predict loss in weight trends necessary to optimize the desired long-term flow rates [19]. There is another aspect which is quite important for understanding operation of the LIW. There will be interruptions in measurement from time to time in LIW. Such interruptions occur during filling up of the upstream hopper. Upon detection of a preset low-level threshold, the controller automatically initiates a refill cycle, and subsequently controls hopper refill by weight. Therefore, there will be fluctuations in their feed rates. Such fluctuations are dependent on the filling capacity, characteristics and bulk density of the materials. During this refill cycle gravimetric feeding is not possible and the controller carries out a volumetric mode of feeding. In this period the discharge weighing system has been rendered "blind," whilst the controller is weighing fresh material into the hopper [19]. For better operations, optional devices such as agitators are used to improve the quality of the bulk material for flow.

2. **Procedure of measurement:** The following are the major steps followed in loss-in-weight measuring systems (Refer Fig VIII/3.2.1-1):
   - An upstream loss-in-weight hopper at intermediate stages is initially and intermittently rapidly filled with the help of an automatic filling valve. At a particular level (predefined set point) or hopper-full weight the filling valve is closed through loss in the weight feeding system controller.
   - When the metered feeding system starts (or is already running during any discharging cycle), it discharges material/product into the process; thus the weight of the upstream product hopper gradually falls, based on the amount of discharge to the process. The falling weight is sampled for measurement at regular frequencies (i.e., every few milliseconds) by the data acquisition part of the intelligent controller already discussed. The said controller process this information (integration over a predefined time period) and is stored as a falling weight per unit time (say) kg per min. This weight per unit time is compared to that already preset by the operator and stored in the memory.
   - Here the preset stands to signify the slope of falling weight per minute. So, any difference between the preset rate and the same actually measured (and processed) is used by the controller is used by the process controller section of the intelligent electronic controller to modify the set point for the speed controller, of the variable frequency drive (VFD) for the drive motor of the loss-in-weight feeder/feeding device. Based on this derived set point, the VFD speeds up or slows down the product feeding device to match the slopes, i.e., to make the two slopes identical [20].
   - When the feeding device discharges, the weight of the upstream hopper will fall. At a preset hopper low weight, the metering feeder will be locked onto its last averaged filling value [20] to allow starting of the filling of the hopper with the help of an autofilling valve, i.e., the autofilling valve will be signaled to open for quick filling of the hopper.

- When the upstream hopper is again filled quickly, the metered feeding system will be reverted back to gravimetric feeding and to automatic control at the original correct speed that was last memorized by the controller during the previous cycle.
- Thus the cycle is repeated. An intelligent controller always goes through a learning process to improve its performance. As mentioned earlier, advanced controllers use interpolation and extrapolation in predicting better accuracies.
- The cyclic operation is depicted by the curve in Fig. VIII/3.2.1-1, which also includes measuring arrangements.

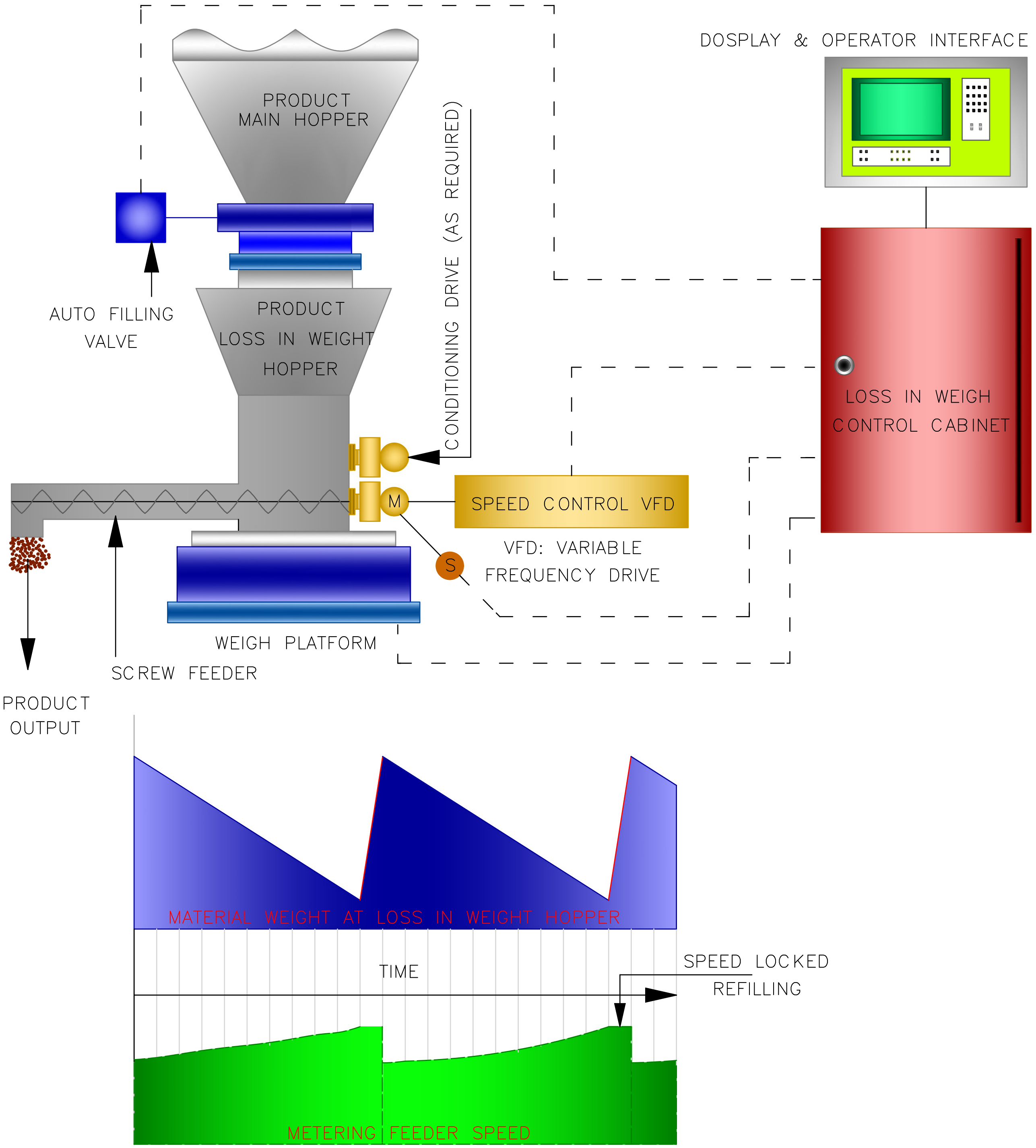


FIGURE VIII/3.2.1-1 Loss-in-weight feeding.

With these basics, we now go into greater depth on the system through descriptive details.

3.2.2 DESCRIPTIVE DETAILS FOR LOSS-IN-WEIGHT MEASUREMENT

A loss-in-weight measuring system is used to measure small and medium flow ranges. They find their maximum applications and usages in the food and beverage and pharmaceutical industries. However, these principles are used in many other industries, and this author has experienced the same in cement applications. A loss-in-weight measuring system involves a gravimetric feeding method for both continuous processes as well as in batch mode processes. This is rather low cost and does not require frequent adjustments and calibration is not needed for compensations as in a belt weigh feeder. The feeding material(s)/product are stored in a hopper located above the feeder/feeding device. As the material is discharged to the process taking the feed from the hopper, it must be replenished from time to time during the measurement cycle but without disrupting the dispensing process. As discussed in Section 3.2.1 above, the entire system (including the hopper) is weighed for LIW operation. For solid material dispensing different kinds of feeders are deployed. For liquid dispensing other dispensing mechanisms may be used. For easing out material dispensing depending on the requirement for accessories such as agitators, rotating bridge breakers, etc. that are used along with their operating motors. Materials of construction for upstream hopper design are determined based on the material/product to be fed and the requirement set forth by the downstream feeding device so as to ensure consistent flow of materials from the storage hopper. We now look into details of the various prefeeders, material delivery, and filling up issues, etc.

1. **Process types:** As indicated earlier, LIW can be utilized for both continuous as well as batch processes. These two processes have different requirements, as specified below.

- *Continuous process:* Loss-in-weight feeding systems are often designed to weigh and control the output of variable products continuously with high accuracy of, e.g., 0.25% AR and ±1% AR on the lower side. For a continuous process, division of the cycle time is important, especially for pharmaceutical industries. From the literature it has been found to be approximately 10:1 running to filling, e.g., 10 min run to 1 min [20]. When refilling in a continuous process it is extremely important that the refill devices, e.g., autofilling valve, must be reliable to maintain constant flow (of either the API or excipient to the process [21]). The flow should be at a sufficiently high rate so as to avoid any chance of exceeding a specific refill time limit. Referring to Fig. VIII/3.2.1-1, when one studies the feeding device speed during refill, one can notice that it is constant as the speed controller is locked. This means that gravimetric flow is not taking place. If the refilling time limit is exceeded, then it will directly impact on the process and product quality may be degraded. Good control is needed to ensure absolutely constant mass flow to maintain product quality when LIW is utilized in mixing processes or extruders in feed.
- *Batch process:* In LIW batching, simultaneous feeding of multiple ingredients in a common collection hopper reduces the overall batch timing. However, each feeding arrangement needs to have a separate set of load cells with high accuracy and must be precisely sized for the ingredient [22]. Therefore, the cost of the system goes up. However, standard loss-in-weight modules with eradicating weigh hoppers and in-flight material are very helpful when the weighing material is very sticky and does not have good flow properties [20]. LIW can also be used for mixing purposes with the help of different types of feeders, as discussed below.

Fig. VIII/3.2.2-1 shows the schematic for application details of LIW to show how it can be used for various process and feeder types.

2. **Feeders types:** There are various kinds of feeders used with LIW. Some of them are described here:
   - *Screw feeders:* The screw feeder is the most common type of feeder for loss-in-weight systems pertinent to solid flow measurement. They are available in various sizes, ranging between 25–250 m with a load-carrying capacity of a few kg per hour to almost hundreds of tons per hour.
   - *Vibratory feeder:* Vibratory trays are mostly used for accurate weighing and metering of free-flowing powders, granular products, or plastic pellets in loss-in-weight solid flow measurement as shown in Fig VIII/3.2.2-1. Normally they have a capacity of up to 30 t/h [20].

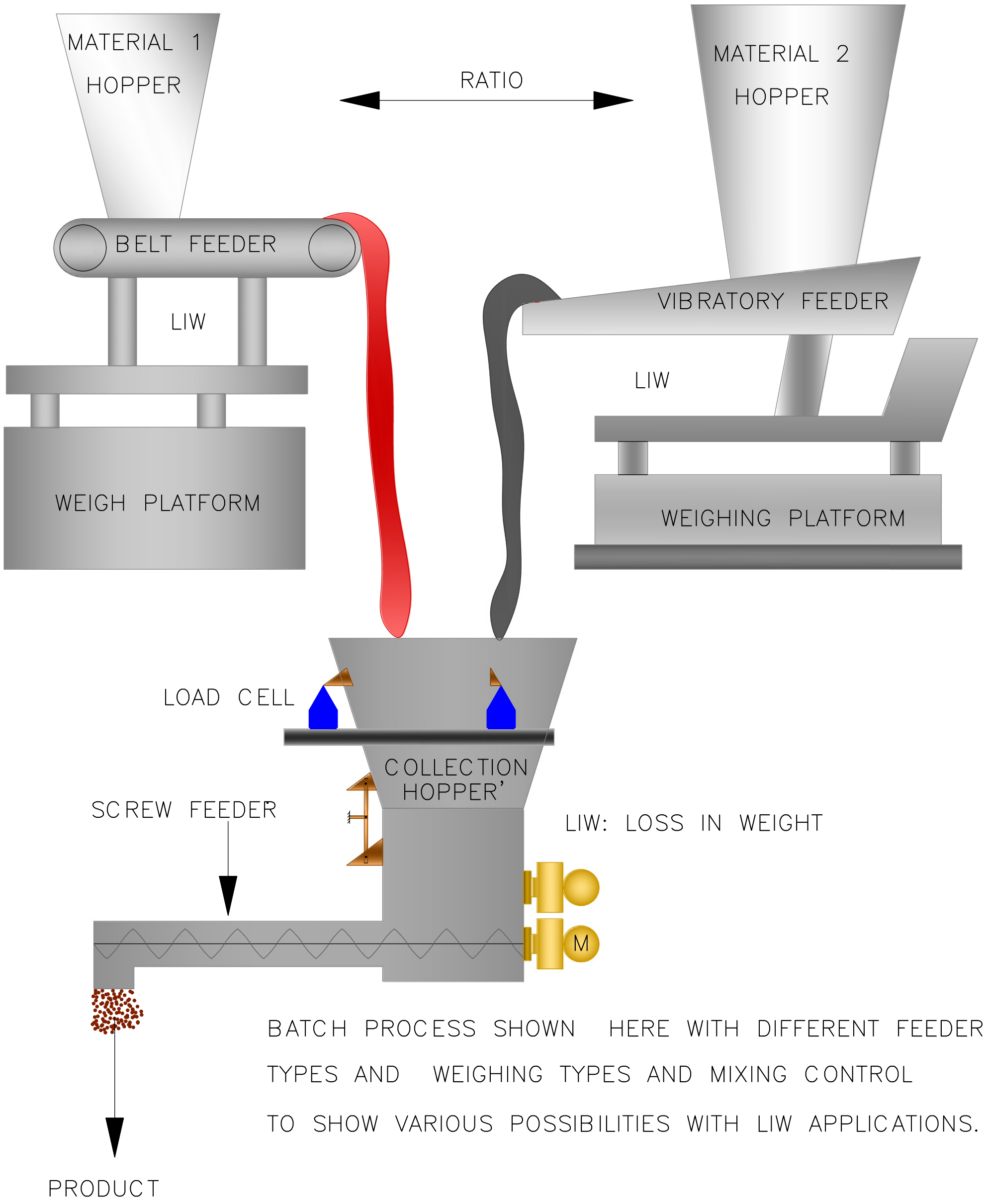


FIGURE VIII/3.2.2-1 Loss-in-weight application.

- *Belt feeder:* As shown in Fig. VIII/3.2.2-1, belt feeders are often used for fragile and friable products, such as fruit and cereal flakes, for loss-in-weight flow measurement methods. In belt feeding weight platforms are most commonly used.

3. **Liquid dispenser:** The loss-in-weight method is also applicable for liquids with a high accuracy of up to 0.5% AR. When liquid dispensing weigh platforms are normally used, as shown in Fig. VIII/3.2.2-2A. This consists of a header tank, flexible connection, and discharge via a variable-speed pump. Loss in liquid weight per unit time is measured by the microprocessor and the pump speed is modulated to hold the liquid's loss-in-weight and thus output constant [20].
4. **Weighing types:** There are several ways to weigh materials and components. Some of these have been enumerated below.
   - *Weigh platform:* These are stable platforms for weighing. As shown in Fig. VIII/3.2.2-2A&B, a weigh platform consists of a robust, frame fitted with high-performance weighing technology with a set of load cells. They have provisions for compensating any off-center loading which may occur during hopper filling and emptying and inaccuracy due to temperature change [20]. Normally these units are compact devices, in an enclosed stainless steel dust cover with protected electronics. They are used for small to medium-sized flow measurements, and they also find application in liquid dispensers as already mentioned. Some of the protection features include but are not limited to overload stops, side-impact stops, and transit locks. A weigh platform is easy to install and they are widely used.
   - *Hopper weigher:* Hopper weighers are very common in LIW applications. In such installations, a loss-in-weight hopper complete with a metering feeder is suspended from a set of load cells to avoid large turning movements [20]. A typical arrangement has been depicted in Fig. VIII/3.2.2-2C and also in Fig. VIII/3.2.2-1 for a collection hopper.

   There is another type of weighing method referred to as the hybrid type, which is normally used for very light materials and that enjoys the advantage of weight balancing.
5. **Performance issues:** Normal accuracy is 0.25% AR–0.5% AR, however better accuracy is possible. There are a few factors which affect the performance of LIW. Some of these issues are discussed in this subsection.
   - *Feeder issues:* Any error in measurement accuracy starts from an error in feeding.

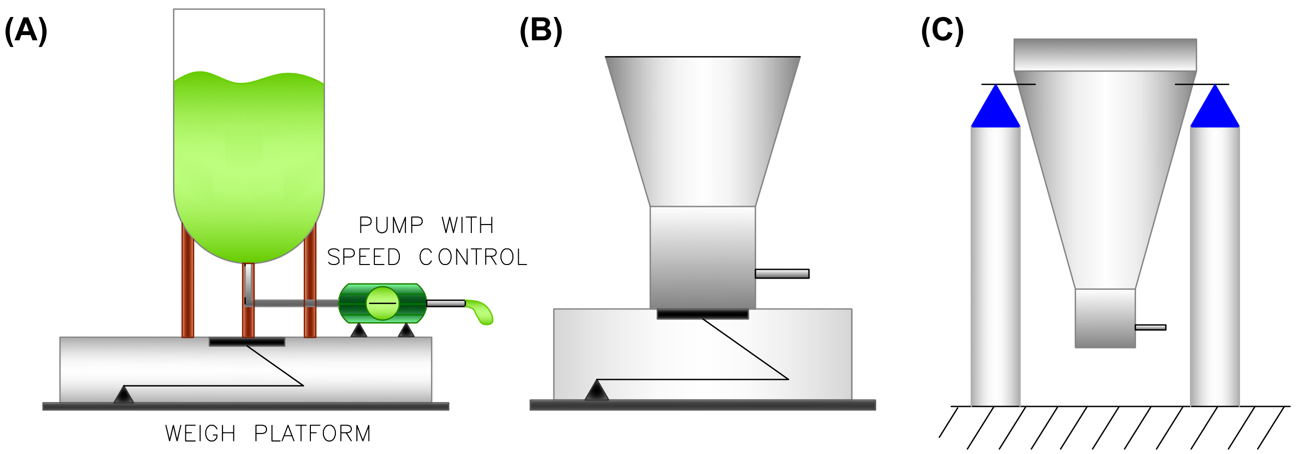


FIGURE VIII/3.2.2-2 Liquid dispenser and weighing types. (A) Liquid dispenser. (B) Weigh platform. (C) Hopper weighing.

Therefore, it is important to select a suitable feeder. Instantaneous flow rate, especially for materials with relatively poor flowability, shows some inconsistencies (pulsating nature) with screw feeders or rotating feeders on account of the filling of screws/cups. However, with respect to total flow, these short-term variations are insignificant in most cases. Vibratory feeders exhibit a very consistent instantaneous flow rate, but only with optimum free-flowing granular materials [19].

- *Material characteristics and flow handling:* From Section 1.2.0 it has been noted that there are different kinds of characteristics for materials. Naturally, the materials with more compacting characteristics may become compacted at the bottom of the hopper due to the material head above it. These materials may bind into lumps in the feeder causing an inconsistent material flow, or stick to the sides of the hopper (causing rat holing), or cause bridging within the hopper [19]. All these cases are responsible for an inconsistent flow pattern and would cause inaccuracy in measurement and make the control functioning difficult. In the case of granular free-flowing solids the problems will be less.
- *Bulk density:* With a full hopper there will be a tendency for the material at the lower part of the vessel to be at a higher density due to compression from the weight of the material head above it. Hence there will be a slight density difference between the material at the lower and upper parts. This tendency is dependent on material characteristics. Free-flowing grains and granular materials will have less of an effect as already discussed in the initial part of this discussion. So, when filling the hopper with an automatic control valve it will affect the measurement to a certain extent, i.e., there will be fluctuations in measurement.
- *Hopper profile:* The internal profile will affect the level in the hopper, which will impact the cycle operation and hence has some effect on metering performance.

After discussing these ideas about loss-in-weight flow measurement methods we now look into the details of various features and applications for loss-in-weight methods.

3.2.3 FEATURES AND APPLICATIONS OF LOSS-IN-WEIGHT MEASUREMENT

In this section, the major features and applications of loss-in-weight (LIW) measuring systems are covered. The discussion starts with features of LIW.

1. **Features of LIW:** Based on the application, there are some variations in the design of loss-in-weight measuring systems. However, generally the following features, including the advantages and limitations, are applicable:
   - *Versatile:* As discussed in the previous section, there are many combination of hopper style, feeder types, and weighing methods with dust-tight all-metal/steel construction possible. Therefore, there is a wide range of LIW available in a variety of models to cater to a wide range of materials with varying characteristics.
   - *Hazardous applications:* Since loss-in-weight measuring systems are available in completely enclosed chambers which enables them to be used in hazardous environments with suitable certifications, e.g., ATEX no. FM, etc.
   - *Modular design:* Loss-in-weight metering is normally of a modular design, which means it is easier for installation and disassembly, which is especially important for applications requiring hygienic cleaning. Also, such modular design and easy access make maintenance much easier.
   - *Metering accuracy:* A meter accuracy of 0.5%−1% is typically available, however better accuracy of up to ±0.2% AR is possible, especially for pharmaceutical applications. Precise accuracy is accompanied by highly reproducible results.

- *Tare weight:* Since in loss-in-weight measurement moment-to-moment weight is sampled for calculating the weight difference, the tare weight is insignificant.
- *External factor:* Measurement is not much influenced by external influences, such as shocks and oscillation.
- *Interface:* adjustable interface to upstream and downstream sides.
- *Material containment:* LIW is very vulnerable when mixing batch mixing etc. are involved with materials with dust, toxicity.
- *Isolation:* Loss-in-weight feeders must be effectively isolated from their environment for accurate weighing. Therefore, flexible supply and discharge connections are necessary, and suitable care is essential.
- *Refill:* During the refilling period weight measurement is not possible. Therefore, for materials whose density does not increase appreciably with increasing head load (such as pellets, for example), the feeder speed can be held constant, but for variable-density powders and granules, the feeder speed may be automatically reduced to gradually slow the feeder speed during refilling. In this connection, the speed curve in Fig. VIII/3.2.1-1 at the time of filling and after filling may be noted.
- *Footprint:* The footprint of the LIW measurement system is small for a low feed rate but varies almost proportionately with the feed rate so that, while adapting the method, space provision should be kept in mind. In fact, for this reason LIW is more suited to low to medium feed rates.

2. **Application areas:** As indicated earlier, loss-in-weight measuring systems are used mainly for small and medium-sized range feed/dosing rates, hence they find major applications in the food and pharmaceutical industries. Major applications are for dosing, feeding, and mixing in continuous as well as batch processes. However, this versatile system is also in use in other industries. Major application areas include the following:
   - *Food industry:* cereals, flakes, muesli bars, sugar mixtures, milk powder, aromatization, to name a few.
   - *Pharmaceutical industry:* Production of various kinds of medicines, vitamins, and tablets.
   - *Chemical industry:* Extrusion premixing, fertilizers, building materials, detergents, pesticides, and other chemical materials with various uses.
   - *Cement:* Not common but used for kiln feed.
   - *Plastics industry:* Film, plastic pallets.
   - Processing of plastic, films, coatings.

   We now investigate how this versatile system can be specified.

3.2.4 SPECIFICATION OF LOSS-IN-WEIGHT MEASUREMENT

The specification for a loss-in-weight measuring system has been given in the tables below. ***It is worth noting that, on account of variations, feeding methods, hopper types, and weighing types there can be wide variations in the specifications. Therefore, it is very difficult to put forward one suitable specification. Efforts have been made to specify the system in a generalized way (for solids mainly). However, the silver lining is that all such variations are mainly on the mechanics. Electronic controllers, VFDs, etc., are common.*** Table VIII/3.2.4-1 gives the specification of a loss-in-weight measuring system in a generic way. It is worth noting that as the specification is a general one. Also, it has been attempted to put the best possible data from different manufacturers, and so there will naturally be a deviation from actual instruments. The specification given is just a guide and the reader should specify the requirements for a specific instrument bearing in mind the application in hand.

TABLE VIII/3.2.4-1 Specifications for Loss-in-Weight Measuring System

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Materials	Powder, grains, granular materials, flakes, and liquid for liquid dosing		
2	Feeding equipment	Varieties of feeders with variable-speed drives. Feeders are, e.g., screw, belt, vibrating, for liquids pump with variable-speed drive		
3	Weighing	Weigh platform, hopper loads cell hybrid type. Measurement by set of load cells		
4	Load sensing	Set of load cell of different design/nonload cell—lever network utilizing heavy-duty stainless steel flexures* for all pivotal connections (with LVDT) (courtesy: Acrison)		*Ratiometric Weight sensing system
5	Speed sensing	Tachometer		
6	Typical capacity	Difficult to specify, as it depends on application from a few kg/h to a few ton/h (e.g., 20 t/h)		As per applications
7	Drive motor	Variable-speed drive with suitably rated motor		
8	Materials of construction	Normally all stainless steel (304/316)/nonmetal parts duly approved by authorities, such as FDA, etc., necessary for food and pharmaceutical industries. For other industries, as suitable for the application, but mainly steel		
9	Level sensing	At refill hopper as per manufacturer's standard—volumetric sensing		
10	Speed control	Normally variable-frequency drive (VFD) at times with voltage and frequency control of required rating for the application.		
11	Refilling action	Automated valve (typical)		
12	Control system	Intelligent control system, e.g., mini PLC, operator interface panel		
13	Output	4—20 mADC, smart version supports: Fieldbus communication (e.g., PROFIBUS/Foundation Fieldbus), some support bluetooth, PC interface and standard links are available, DeviceNet/Control Net		
14	Output function	Rate flow, totalized flow, alarm, remote reset, control function in continuous process; batching and blending functions		
15	Display and operator function	Digital display, operator reset, calibration, HMI support, control and programming. Remote intelligent electronics cabinet and local control panel		
16	Electronic cabinet	Remote intelligent electronics cabinet and local control panel with operator interface. Aluminum/MS different grades		

Continued

TABLE VIII/3.2.4-1 Specifications for Loss-in-Weight Measuring System—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
17	Enclosure class	IP65		
18	Power supply	Standard power supply 240/110 VAC 50/60 Hz/24 VDC		
Performance and Other General Details				
19	Accuracy	Ranging between 0.2% AR to 1.0% AR based on application and manufacturer's standard		
20	Ratiometric weight resolver*	0.1% linearity for weight resolving		*Refer to remarks of SL. 4
21	Turndown	10:1 to 15:1		
22	Field calibration	Remote panel; frequent calibration unwarranted		
23	Application	Major application area includes power and cement plant and pharmaceutical plants but for other plants refer to Subsection 3.2.3.2		
24	Accessories	Agitator and/or other material conditioning device		
25	Special Feature	To specify – If any		

3.2.5 LOSS-IN-WEIGHT MEASUREMENT WITHOUT A LOAD CELL

From the literature one can see that there is another kind of loss-in-weight measurement, where in place of the load cell, the load is sensed by an LVDT, somewhat similar to that described in the case of an impact flow meter. Here the issue is slightly more complicated because in this case the displacement of a single member is not monitored but rather the entire structure, as shown in Fig. VIII/3.2.5-1. Other than this, the basic principles of LIW are the same, only the load-sensing method is different. In place of a load cell it utilizes some of the movements of members and utilizes the same in sensing the load with LVDT, which is connected to the control system. Since the principle of operation is the same as LIW discussed above it is not repeated here, only weight measurement is elaborated on here. In this type the basic weighing system design is a major issue. The system is configured as a modified parallelogram type lever network utilizing flexures for all pivotal connections, which in this case is based on Acrison's technical information based on Ref. [23]. This frictionless weighing mechanism is extremely rugged in construction and so is stable and precise in operation in weight sensing. For stability of operation the weighing system is also counter-balanced so that only the net weight of the material in the metering/supply hopper or tank is weighed.

There are two (one in the reverse side) primary flexures: (1) connect the principal lever beam to the main feeder structure, with two (one in the reverse side) secondary flexures (2) connecting the actual supply hopper (or tank) to the principal lever beam. In addition, two to four linkage flexures connect the lower portion of the supply hopper (or tank) to the main feeder structure. These flexures are identified in Fig. VIII/3.2.5-1with numbering 1, 2, and 3, respectively. These stainless

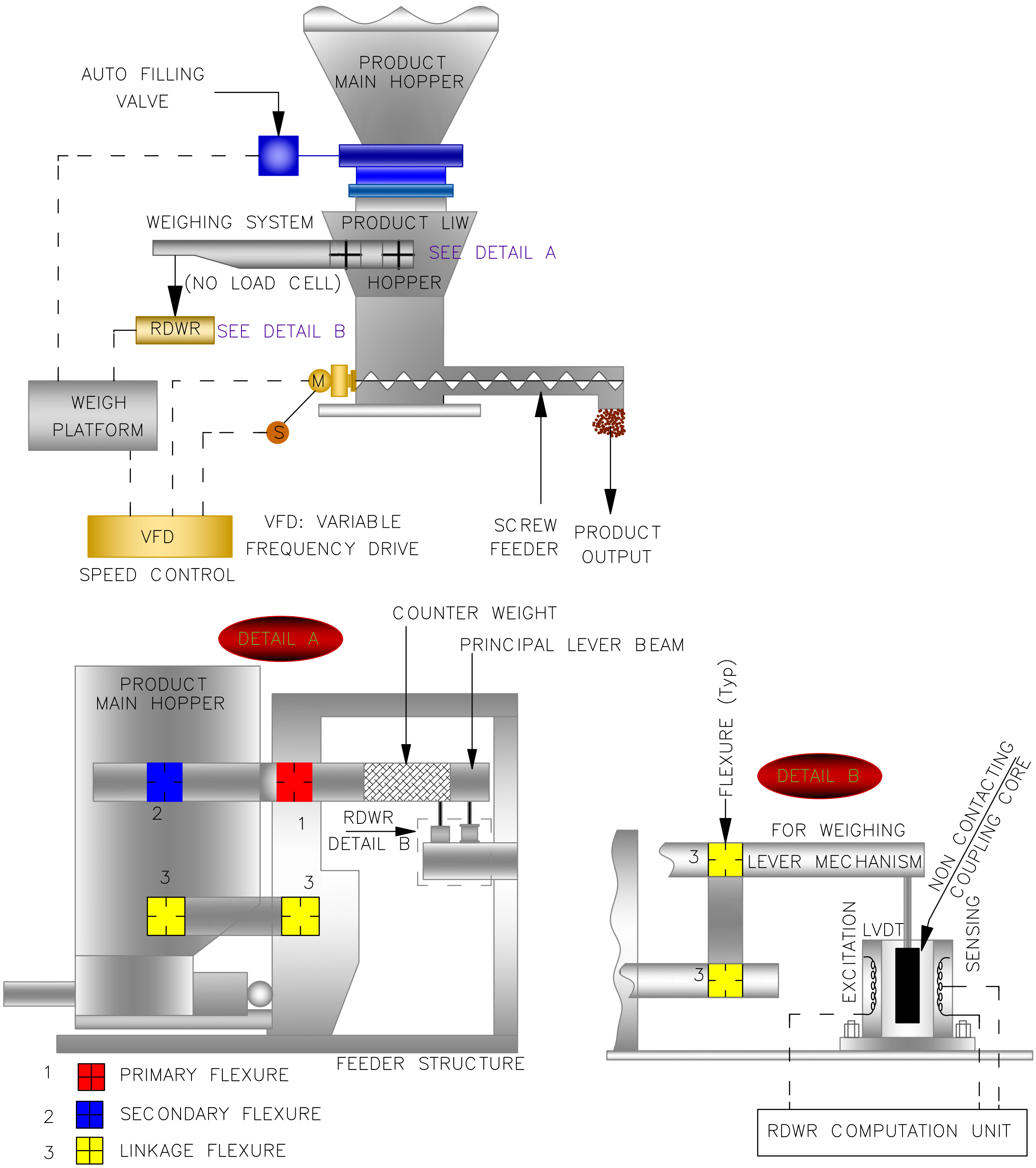


FIGURE VIII/3.2.5-1 LIW feeding without load cell. *Developed based on Acrison documents: Weigh Feeders "Weight-Loss-Differential", in: Model 402,404,405,406 and 408 Series; Bulletin 893, Acrison®.* http://acrison.com/acrison/literature/product-literature/download/; *Weigh Feeders "Weight-Loss-Differential", in: Model 403 Series; Bulletin 728, Acrison®.* http://acrison.com/acrison/literature/product-literature/download/. *Courtesy: Acrison.*

steel flexures provide optimum structural rigidity of the lever network and permanence of the weighing systems' accuracy and calibration. When weight is added to, or subtracted from, the metering mechanism/supply hopper, the lever network "moves" in an extremely precise relationship to that weight. This movement is sensed by the ratiometric digital weight resolver (RDWR) detailed in "detail B" in Fig. VIII/3.2.5-1, and instantaneously converted into an equally precise signal directly proportional to the weight. In RDWR, the physical sensing element does not attach to any part of the lever network and, therefore, cannot be damaged by any amount of shock, overload, and/or abuse that the weighing system may experience.

The question is: *why* this system? On account of it being a less costly proposition many manufacturers often opt for weighing scales for LIW. It is not at all uncommon that there are problems, including maintenance-intensive operation, due to the delicate and temperamental nature of the weighing systems [23]. The most common difficulties are feed rate drift, primarily due to the inability of the feeder's weighing system to remain precise, i.e., loss of calibration. Obviously these issues greatly affect the process formulations and hence affect the quality of the product. In such a situation it is necessary to recalibrate the system. On the other hand, in the flexure movement method utilizing RDWR recalibration is almost zero, hence product quality does not suffer and there will be less downtime, and so overall it may be proved to be beneficial. The major benefit comes from very high accuracy of measurement at around 0.25% AR for a continuous process and 0.1% AR to 0.5% AR for a batch process. Also, there is no requirement for rezeroing. RDWR is the heart of precise load measurement and is connected to an intelligent controller to obtain high accuracy. For further details Refs. [23,24] may be referenced.

It is now time to conclude discussions on the loss-in-weight measuring system. Also, the discussion in this section comes to an end with the belt weigh feeder, which is the most commonly used solid flow-measuring device.

4.0.0 BELT WEIGHING SYSTEM

The belt weighing system is basically a generic term representing in-motion weighing when the material is being conveyed by a belt conveyor/feeder. Anything moving on the belt and the material weight is measured. Another way of looking at it could be measuring the weight of material in a selected section of the belt and measuring the speed of the belt movement flow or feed rate can be computed. The same is done in the belt type gravimetric feeder discussed in Section 3.1.0. Therefore, belt weighing is nothing new. From a functional or operational point of view there is really no difference between the terms weigh feeder, belt weigh feeder, belt gravimetric feeder (already covered in a previous section). Also, in all such cases belt feeders are utilized for conveying materials. However, there are some differences between a belt scale/belt weigher or a weigh belt and weigh feeder. In the case of a belt scale/belt weigher or weigh belt, the belt speed is constant (but not controlled), varying the load-wide flow of material. The computation unit computes the flow by multiplying the sampled weight signal and speed signal and then integrating the same over unit time as desired (per second/minute/hour). Weigh feeders and belt gravimetric feeders also operate in the same way as a belt gravimetric feeder and weigh feeders, however the speed is not constant but instead is regulated and variable to ensure the desired feed rate. Therefore, the computational unit is replaced by a controller and computation unit. Functionally there is not much difference between a belt scale/belt weigher and a weigh feeder, but from an application point of view there are some differences. As discussed above, belt type gravimetric feeders are mainly used for conveying crushed materials in power and cement plants, whereas weigh feeder are used for many other applications across numerous industries. Generally lengths of weigh feeders are greater than those of belt type gravimetric feeders but they are shorter in length than belt scale/belt weighers. However, there are a few

differences in nomenclature and usage only. In this section discussions will be on weigh feeder and belt scale/belt weigher weighing. In both systems the weighing is in-motion type and weighing is carried out without interrupting the main process.

4.1.0 Weigh Feeder Systems

The weigh feeder discussed here refers to a belt weigh feeder. There are other weigh feeders, such as apron weigh feeders, screw weigh feeders, etc., which are discussed separately. These weigh feeders are used for continuous gravimetric feeding of bulk solids conveyed through a belt feeder. These are used for feeding and weighing a wide variety of materials with an accuracy as high as 0.25% AR. They are available in open as well as in dust-tight enclosures. There are three to four major components of the weigh feeder as far as instrumentation is concerned. These are the weigh scale and speed sensor, controller and integrator, and drive for speed control. In this section discussions on the weigh feeder are covered. The discussions start with a recap of basic operation principles already discussed in connection with the belt type gravimetric feeder.

4.1.1 DISCUSSIONS ON OPERATING PRINCIPLES

Weighing feeders are a type of in-motion means of weighing bulk material being conveyed in a belt feeder. The weigh feeder also provides a means for controlling the rate of flow with the help of speed control of the drive for the feeder. Therefore, it is essential for weighing the material passing over a selected isolated section of the feeder, i.e., the system requires accurate transmission of the product load (to the desired section of the feeder) to the load cell. The vertical component of the applied force is measured. When material moves over the weighing scale, it exerts a force proportional to the material load through the suspended idler directly to the load sensor or load cells when excited. In order to protect the load cell/sensor from failure due to overload, the vertical movement of the load cells is limited by the positive overload stop. The output of the load cell is monitored or sampled at high frequency and sampled signals corresponding to weight are transmitted by remote electronics. For computation of feed rate another input from the speed of the conveyor is necessary. This is a signal proportional to the speed of the belt feeder. When these two signals are multiplied the resultant signal corresponds to the instantaneous feed rate. In the integrator instantaneous feed rate are integrated over desired unit time to get the feed rate in terms of mass per second/minute/hour. Since the force measured by the load cell is represented as weight per unit length, it can be multiplied (calibrated) by the distance of the belt travel, e.g., one speed sensor pulse to provide product weight for that segment of the belt. Belt weigh feeders are controlled by an intelligent controller which can be mounted on the frame and or be remote. It is the job of the intelligent electronic controller to calculate the required speed of the motor (speed demand) for the time of the discharge. The speed demand for the weigh feeder controller is produced from the error generated as the difference between the set feed rate and the measured bulk material mass (calculated by the multiplication of load and speed signal) integrated over specified time. The speed demand signal generated at the weigh feeder controller acts as the speed set point for the speed controller. This speed set point is compared with the actual measured speed at the VFD to produce output to regulate the speed of the driving motor. So, finally with the help of a speed controller, e.g., a variable frequency drive (VFD), the speed of the belt is regulated. Therefore, when there is less material on the belt, the feeder will move with higher speed, and the more material on the belt, the slower the feeder speed to cater to

the desired feed rate. Thus the weigh feeder operation cascade mode of control is deployed. Intelligent controllers of weigh feeders need to interface with process control systems for rate flow as well as integrated flow. Quite often it is necessary to integrate a numbers of feeders in one process with the help of smart data transmission and communication. To conclude the discussions on functional aspects of weigh feeders one may argue that this versatile weighing solution for solid flow measurement is capable of performing the following functions:

- Deliver materials at the desired flow rate into or out of a process;
- Monitor, indicate, and record flow rate of material;
- Totalize material for inventory monitoring;
- Active participation for quality control for material batching;
- Production monitoring and regulation.

4.1.2 DESCRIPTIVE DETAILS OF WEIGH FEEDERS

For measurement and control, a weigh feeder basically consists of the following components:

- *Weighing and speed sensor:* With the help of load sensors and speed sensors, weigh feeders monitor and control the flow rate of gravity-fed material from a prefeed device, such as a bin or conveyor;
- *Controller and integrator:* These collect the data from the weigh feeder and output, i.e., flow rate (maximum and minimum), belt load, belt speed, and totalization;
- Variable-frequency drive/converter required for controlling feed rate.

All these parts are depicted in Fig. VIII/4.1.2-1.

Apart from the above instrumentation issues, in the case of weigh feeders the mechanical details are also important. Since various sensors, i.e., load and speed, and controllers, are most important from an instrumentation point of view, these will be discussed separately in subsequent sections. The discussions start with the mechanical and constructional details. ***It is worth noting that the descriptions given below are applicable for both weigh feeders as well as belt scale/belt weighers.***

1. **Major mechanical parts of a belt feeder/scale:** The major mechanical parts of a belt feeder have been illustrated in Fig. VIII/4.1.2-2.

   It is important to note the title of Fig. VIII/4.1.2-2, which represents both the belt weigh feeder and belt scale/belt weigher. We now have a short discussion on the various mechanical parts of a belt weigh feeder.
2. **Construction types for a belt feeder/scale:** Materials of constructions are decided upon dependent on the application and environmental conditions. Normally these are made from mild steel that has been duly treated and painted. There are some applications where for sanitation uses, stainless steel is also used. There are two types from a constructional point of view: open and enclosed types. The selection of which type of weigh feeder to use not only depends on the application but also, at times, guided by local government regulations.
   - *Open type:* In the open type the material exposed to the outside environment. Open style units are used in wash down in critical applications in the food and chemical process industries.
   - *Enclosed type:* These are used mainly used for controlling dust pollution and environment contamination.
3. **Inlet hopper design:** The inlet to belt feeder/belt scale/belt weigher is an important aspect that helps “mass flow,” i.e., it ensures uniform discharge from the bin so that material does not remain in the bin and become compacted, solidified, or expired. It is beneficial to use a slot outlet or wedge type hopper for “mass flow.” A critical issue associated with the mass flow hopper is its

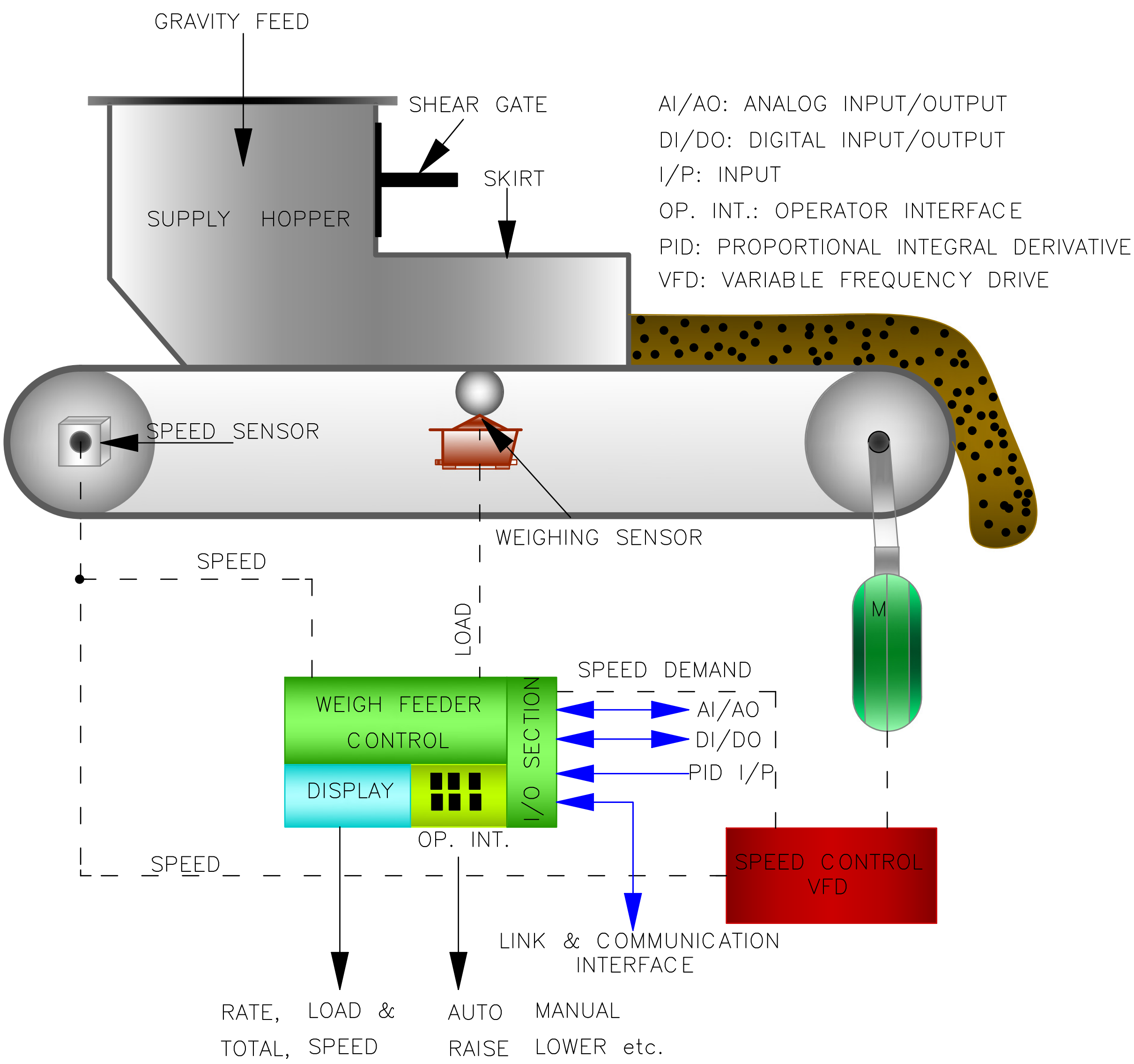


FIGURE VIII/4.1.2-1 Weigh feeder parts and control details.

design. This should be designed in such a way that the feeder must withdraw product from the full cross-section of the hopper outlet. With a longer slot design it may not be possible, because the feeder under a slot will typically withdraw product from a small area at the slot. Therefore, "mass flow" can be achieved by ensuring feeder withdrawal of product from the full cross-section of the hopper outlet. Also, it is necessary to make the capacity of the feeder increase in the direction of discharge. For this, a properly designed interface between the slot outlet of the hopper and the belt is required to ensure that the hopper discharges more product onto the belt along its length. In a well-designed interface, the product flows down through the interface with stresses more or less horizontal. The vertical stresses acting through the shear plane are relatively low. This allows the belt to shear the product efficiently with a minimum amount of force [25]. For a set of conditions such as product type and angle of friction, the hopper slope

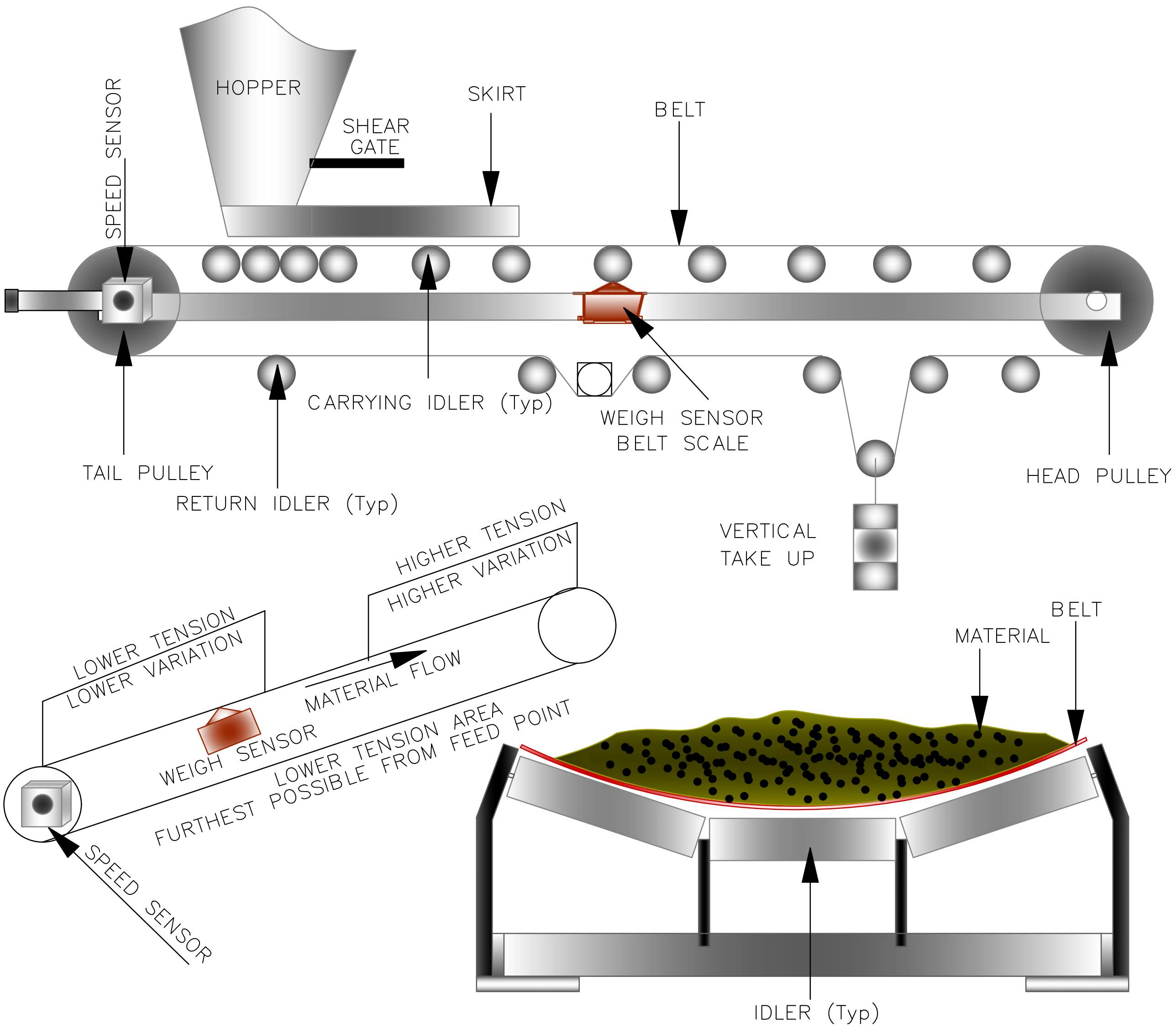


FIGURE VIII/4.1.2-2 Mechanical details of belt feeder with sensors.

ensures mass flow at the side of a wedge hopper is significantly flatter than a conical mass flow hopper. A flatter mass flow hopper will always translate into lower headroom and a more economical design [25]. In "funnel flow," material will support itself and rat holes or bridging can occur. "Mass flow" type design avoids rat holing, bridge formation, etc. For further guidance ref [3] may be referenced. In this connection, Fig. VIII/1.1.0-3 may be referenced.

4. **Shear gate for a belt feeder:** The shear gate is used for setting the bed depth on the belt. The shear gates are electrically operated by a drive motor, and are adjustable for controlling bed depth. There are two main kinds of design, one is the flat shear gate and the other is a half moon design (at the bottom). The flat gate allows greater volumetric flow but also allows more material to come into contact with the skirt board as discussed later. For abrasive materials, as per the half moon design (at the bottom) there will be minimal chance for material to come into contact with the skirt board. Naturally, the half moon design allows consistent flow

and is usually recommended. In the case of an avalanche it can make consistent flow. Any adjustment to the shear gate is only allowed when it is electrically disconnected.

5. **Skirt/skirt board:** The importance of a skirt board or skirt in short is immense as it is responsible for material containment along the belt and is an absolute necessity for weighing consistency and accuracy. The skirt should be well flared out to avoid any plugging and jamming of materials. Since it comes directly into contact with material, it is important to select suitable material for the skirt board. Stainless steel is commonly used as a skirt board material when corrosive materials need to be handled [3].
6. **Belt and belting:** Generally, weigh feeder belts have uniform weigh feeder quality, and an endless belt type for optimum weighing accuracy. Belting with a vulcanized or recessed mechanical splice has solid flanges or corrugated sidewalls to retain material. The weigh feeder/belt scale/belt weigher belts should be of consistent cross-section over their entire length. An endless style belt requires a cantilevered weigh feeder frame for belt removal [3]. Weigh feeder belts are normally supported on flat pans, bars, or idlers to minimize the effects of tension and temperature. The temperature specifications of the belt and of the weigh feeder should never be exceeded for dissipating heat through the belt. Nitrile, thicker rubber thinner polyurethane, or silicone, etc. are used as belt material. The belting and belt materials should be selected based on the relevant application. Often *rip detectors* are used to detect belt damage from sharp or abrasive materials, e.g., in a coal-handling plant in a power generation unit.
7. **Drive and driven pulley:** The pulleys of the belt feeder are crowned for positive belt tracking. Normally, an oversized diameter pulley with rubber lagging provides positive traction and lower belt tension for improved weighing accuracy. For conveying materials without slipping, drive pulleys have lagging, whereas driven pulleys do not require this, however for short conveyors, the driven pulley should also be lagged to avoid changes in belt tension due to concentricity [3]. Pulleys can be welded to the shaft. Associated standards are available from the Conveyor Equipment Manufacturer Association (CEMA): Standards B105.1 and 501.1.
8. **Idler and scale idler:** Idlers are meant to support the belt. Idlers normally follow Conveyor Equipment Manufacturer Association (CEMA) standards for conveying materials. According to the CEMA there are several categories of idlers, e.g., troughing idler, picking idler, return idler, to name a few. These idlers are available in various trough angles, such as 20, 35, and 45 degrees. There is a separate kind of idler for scaling, normally known as the scaling idler. For scaling purposes, the idler for scaling and one before and after the scaling idler should be of scaling quality. The various parts of the scaling idler include but are not limited to the idler frame, for weighing: static beam, dynamic beam, scale mounting bracket, and idler pin. Precise idler alignment is very important for achieving better accuracy of the weighing system. Any misalignment of idlers will result in unwanted forces being applied on each idler in the weighing area, causing calibration and measurement errors. Scale idlers can be a single scale idler in modular design used for a short-length belt feeder and multiscale idlers used for longer-length belt feeders.
9. **Bearing:** The pulleys are mounted on the weigh feeder frame on bearings. Bearings should be self-aligning to ensure bending stresses do not prematurely fatigue the welds on the pulley face. Flange or pillow block style bearings are normally used. Bearings can be ball or spherical roller bearings with labyrinth seals for longer service life.

10. **Motor and reducing unit:** AC or DC type motors can be used. The motor can be mounted with a flange or may be foot-mounted. Normally, inverter duty motors are used to cater to the requirements of turn-down ratio or rate range. The rating should be higher than the actual power requirement for the application by using a suitable factor based on the application history. A constant torque (a load characteristic where the required torque is constant regardless of the speed) motor is used. The motor design is largely based on efficiency and torque [3]. The requirement for a gear reducer comes from the fact that the motor runs at high speed, 1500−1800 RPM, and should be reduced to meet the speed suitable for belt travel speed for accurate weighing and conveying. The gear reducer sizing is dependent on many factors, such as belt width, material profile, conveyor length, material bulk density, and in-feed length, as well as motor power, shaft size, bearing size, and environmental conditions. It is recommended that the torque required by the application be met with a minimum of a 1.3 safety factor.
11. **Miscellaneous other electromechanical components:** Apart from the major components of the belt feeder discussed above there are a few other items also as listed here:
    - *Belt tensioner:* This is required to remain constant during operation.
    - *Belt scraper:* This is required to keep the belt clean during operation, and when effective there is no build up.
    - *Belt plow:* This keeps the belt clean during operation and is critical for reliable conveying, as material can build up on the pulleys and create a change in tension.
    - *Track/sway switch, zero speed switch:* These are various switches needed for belt feeder operation to avoid misalignment and sensing lack of speed (refer to Section 4.7.0).
12. **Load sensor:** Refer to Section 4.3.0.
13. **Speed sensor:** Refer to Section 4.4.0.
14. **Integrator and controller:** Refer to Section 4.5.0.
15. **Motor speed control for feeder:** Refer to Section 4.6.0

4.1.3 FEATURES OF WEIGH FEEDER (ALSO BELT SCALE/BELT WEIGHER)

There is commonality between a weigh feeder and belt scale/belt weigher, and they have common features. However, in the case of a weigh feeder the main drive has speed controls, with the help of a variable-voltage variable-frequency (VVVF) or variable-frequency drive (VFD; for major uses) mainly used. However, in the case of a belt scale/belt weigher, a fixed-speed drive will suffice. Listed below are a few major features of belt feeders applicable for both weigh feeders and belt scale/belt weighers.

1. Open or fully enclosed designs are possible to cater to the various application requirements.
2. Modular design with possible wide variation of length/width (choice widths).
3. Belt scale/belt weighers are comparatively easier for installation.
4. Flanged in-feed section with varieties of inlet hopper designs for better material extraction for a wide variety of material properties.
5. Cantilevered frame for quick and easy removal of vulcanized endless belts for cleaning and maintenance.
6. Construction material, such as mild steel carbon steel or stainless steel construction.
7. Belt and pulley strippers to ensure no dirt contamination.
8. Lubricated idler in pivotless weigh frame for longer life for some weigh feeder supplies.
9. Some with advanced belt tensioner for better accuracy.
10. Adjustable feed rate maximum range and rangeability as per manufacturer.
11. Turndown ratio 1:10 standard; 1:20 available.
12. Digital tachometer with incremental encoder for better measurement and control accuracy.
13. Easy calibration and adjustment of zero point.

4.1.4 APPLICATION OF WEIGH FEEDER (ALSO BELT SCALE/BELT WEIGHER)

It is needless to say that the weigh feeders have wide areas of application in various plants; with weigh feeders finding applications in almost all process industries and many other plants. They are used for process control in cement plants, smelting plants, blending controls, batch controls, and production controls in manufacturing industries. A few major areas of applications are listed here:

1. **Material handling:**
   - Limestone;
   - Coal;
   - Lignite;
   - Iron ore;
   - Other ore and minerals;
   - Food grains;
   - Sulfur;
   - Gold concentrate;
   - Clinkers and others;
   - Clay and shale, etc.;
2. **Cement plants.**
3. **Aggregate.**
4. **Food industries.**
5. **Pharmaceuticals.**
6. **Power plant and/or coa/lignitel handling plant.**
7. **Mining.**
8. **Steel and smelting.**
9. **Chemical plants.**
10. **Agriculture.**
11. **Tobacco.**

4.1.5 SPECIFICATIONS OF WEIGH FEEDERS

Specifications for weigh feeder are given in Table VIII/4.1.5-1. It is worth noting that as the specification is a general one, all the data will not necessarily match with any particular instrument chosen. Also, it has been attempted to put the best possible data from different manufacturers, and so there will naturally be a deviation from actual instruments. The specification given is just a guide and the reader should specify the requirements for a specific instrument bearing in mind the application in hand.

TABLE VIII/4.1.5-1 Specifications for Belt Weigh Feeder

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Solid type	Chunky solids, or crushed solid ores/coal, clinker, grains, fine solids, flakes, etc.; wide range of solid materials		
2	Feeding equipment	Wide varieties of hopper/bin of suitable design and/or silos with discharge valves		
3	Design/ambient temperature	Design: maximum 90°C; Ambient: −20 to 60°C		
	Typical capacity	As low as 0.1 t/h to 2000 t/h, depending on manufacturer and applications		As per manufacturer standard
4	Belt length	Wide variations available, such as from 1.5 m to nearly 2 m common. Based on application*		*Manufacturer standard
5	Belt width	Typically 450−1400 mm		

Continued

TABLE VIII/4.1.5-1 Specifications for Belt Weigh Feeder—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
6	Major components	Head pulley: rubber lagged Idler: CEMA standard; size, angle application based Scale idler: single/multiple (as per application); standard: CEMA Reducer: shaft mounted Belt: endless polyester, vulcanized rubber and other as mentioned in Section 4.1.2 Frame: cantilever Belt load: dependent on material	To specify	
7	Load span	Manufacturer standard	To specify	450 mm (tYP)
8	Materials of construction	Belt: Refer to Section 4.1.2 Frame: MS/CS/SS		
9	Sensing and control	Load sensor as per Section 4.3.0; speed sensing as per Section 4.4.0; integrator as per Section 4.5.0; and controller as per Section 4.6.0 Motor control as per Section 4.7.0		
10	Drive	Shaft mounted; AC/DC inverter motor		
11	Speed control	Normally VVVF or VFD		DC drives are also seen
12	Output	4–20 mADC, cumulative pulse frequency and smart version supports: Fieldbus communication (e.g., PROFIBUS/Foundation Fieldbus), some support bluetooth, PC interface and standard links are available		
13	Output function	Rate flow, totalized flow, alarm, remote reset, zero adjustments, control function in continuous process; batching and blending functions		
14	Display and operator function	Digital display, operator reset, calibration, HMI support, control and Programming. Remote intelligent electronics cabinet and local control panel		
15	Electronic cabinet	Remote intelligent electronics cabinet and local control panel. Aluminum/MS different grades		
16	Power supply	Standard power supply 240/110 VAC 50/60 Hz/ 24 VDC		
Performance and Other General Details				
17	Accuracy	Overall 0.5 % AR standard; better possible; nonlinearity, hysteresis: <0.02% AR		
18	Reproducibility	0.02% AR		
19	Turndown	10:1 to 20:1		
20	Field calibration	Supplied with test load		

Continued

TABLE VIII/4.1.5-1 Specifications for Belt Weigh Feeder—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
21	Accessories	Belt scrapper, zero speed, sway switch, etc. as required		
22	Special feature	To specify – if any		

In this table mainly the mechanical part of weigh feeders have been elaborated. Electronic components like weigh/speed sensors and integrator controls have been specified separately in Sections 4.3.0 through 4.7.0 to cover both weigh feeder and belt scale/belt weigher.

4.1.6 WEIGH FEEDER SELECTION GUIDE

It is imperative to marry the process requirements with the technical data for the selected device. A short discussion on the selection procedure has been enumerated below. Therefore, it is essential to first establish the plant requirements.

1. **Application requirements:** For selection of a weigh feeder the following system requirements should be specified or noted:
   - *Flow rate:* Maximum/minimum;
   - Particle size;
   - Material temperature;
   - Material bulk density;
   - Special material characteristics, such as abrasion, adhesion, causticity;
   - Ease of installation and maintenance;
   - Technical and system support;
   - Intelligent electronics and its interface.
2. **Major selection criteria:** The following are the major selection considerations:
   - Solid material class, namely, bulk material, fruits, grain, etc.;
   - Industry type;
   - Whether sanitary version need;
   - Idler loading (CEMA class);
   - *Scale idler (CEMA standard):* Single/multiple;
   - Belt tension and wrap;
   - Motor power requirement and sizing based on mechanical data with tolerance;
   - Shaft deflection and stress;
   - Sensor accuracy and effect on overall measurement;
   - Accuracy class;
   - Turndown ratio;
   - Approval requirements.
3. **General discussions:** For fragile materials the use of horseshoe style inlets is recommended for better protection. The use of other options, such as corrugated side wall belts with no skirt boards should be avoided if material can pack in the sidewall causing contamination or damage [3]. Apart from these load cell types, the sensing method and temperature compensation are also issues that need to be looked into. Test load and calibration issues are also important in selection.

4.1.7 WEIGH FEEDER DISCUSSIONS

Weigh feeder performance and factors affecting performance of weigh feeders are extremely important; a number of such issues have been enumerated below:

1. **Weigh feeder performance:** Repeatability, linearity, and stability are major factors responsible for weigh feeder performance.
   - *Repeatability:* This represents the consistency of the weigh feeder discharge rate at a given operating point, i.e., the expected variability of the discharge and hence the quality assurance of the product itself.
   - *Linearity:* Linearity is represented by a straight-line correspondence between the set point and the actual average feed rate throughout the feeder's specified turndown range. Linearity reports how well the feeder delivers the desired average rate throughout the feeder's operating range.
   - *Stability:* A perfectly performing feeder needs to maintain the performance over a long period.

2. **Measurement stability:** Factors on which stability depends normally include feeder type, control and weigh system stability, the handling characteristics and variability of the material, the feeder's mechanical systems, maintenance, and the operating environment itself. Drift is detected by calibration checks, and is typically remedied by a simple weight span adjustment.
3. **Factors affecting performance:** Factors that affect the performance of the belt weigh feeder include the following:
   - Consistency of material bed (performance of shear gate);
   - Material property and feed rate range desired;
   - The resolution, responsiveness, and sensitivity of the weigh feeder;
   - Mechanical constructional geometrical details of the weigh feeder as well as proper use of other mechanical parts, e.g., belt tensioner (to avoid tension variations) and belt scrapper;
   - Effectiveness of electronic controls of the weigh feeder in terms of speed control.

   Weigh feeder accuracy depends on many factors discussed above, starting from the in-feed. The inlet hopper design and shear gate are mainly responsible for meeting the consistency in bed height. Other important issues are environmental sensitiveness of the weigh feeder, including ambient temperature, vibration, and shock resistance. Temperature-withstanding capability of the feed system and material temperature. While static belt take-up tensioning devices may still be found on some feeders, the preferable solution is a dynamic tensioning device that applies constant tension regardless of belt load, wear, and stretch [26]. Periodic taring is crucial, especially where there is the chance of material build up and adherence of material to the belt. Also, automatic track switch and sway switch, as accessories, play important roles in preventing misalignment so that measurement is not affected. The phenomenon of transportation lag has relevance in some weigh belt feeding applications [26].

4.2.0 Belt Scale/Belt Weigher System

As noticed earlier that except speed control (applicable to weigh feeder) there is not much difference between belt scale and weigh feeder. Thus the belt scale/belt weigher is basically meant for measurement, whereas the weigh feeder does both measurement and control. In view of this it is needless to tell that ***depending on applicability, the details given in Section 4.1.0 for the weigh feeder are also applicable for a belt scale/belt weigher, and hence are need not repeated here.*** Also, as the weigh feeder has feed rate controls, better accuracy is expected from it. Therefore, the reader needs to go through previous sections carefully (except the control part that is not applicable for belt scale/belt weigher), some additional discussions on belt scale/belt weigher have been put forward.

4.2.1 FUNCTIONAL ASPECTS OF THE BELT SCALE/BELT WEIGHER

Except for the control part, the basic principles of operation of the belt scale/belt weigher are the same as those described in Section 4.1.1. As stated above, the weigh feeder is mainly associated with controlled flow applications (process control, batch, blending control), whereas the belt scale/belt weigher is associated with flow monitoring and accounting. Functionally, belt scale/belt weighers are used for the following purposes:

- Indicate the flow rate of material input for the process, during processing and/or for final product;
- Totalize material for inventory monitoring;
- For loading/unloading of truck, ship rail, or car;
- For custody transfer purposes;
- Provide quality control for material batching;
- Production monitoring and accounting (on daily, shift basis).

Basically, with the help of heavy-duty load cells measuring the load on belt conveyor idlers, then multiplying the load with the speed feed rate is computed, which is very similar to a weigh feeder. The belt scale/belt weigher is a weighing solution comprising the following parts:

1. **Scale:** Load cell placed on weighing idler to monitor load on belt section;

2. **Speed sensor:** Monitors the speed of the conveyor belt for computation purposes;
3. **Integrator:** This is basically one electronic monitor meant to collect data, compute, display (and operate):
   - Flow rate;
   - Belt load;
   - Belt speed;
   - Totalization.

   Generally, belt scale/belt weighers are deployed for batches or samples greater than 10 min in duration.

4.2.2 DESCRIPTIVE DETAILS OF BELT SCALES/BELT WEIGHERS (ADDITIONAL DETAILS)

The descriptive details of belt scales/belt weighers as described in Section 4.1.2 are applicable to the belt scale/belt weigher also, and hence are not repeated here. In this case also, details regarding load, speed, and integrator are discussed in Sections 4.3.0 through 4.5.0. A few pertinent issues for the belt scale/belt weigher are discussed here:

1. **Belt conveyor contour:** A belt scale/belt weigher can be quite long. Based on the belt conveyor contour there are various types, as shown in Fig. VIII/4.2.1-1, such as:
   - *Horizontal:* In this contour the entire belt conveyor is in the horizontal direction;
   - *Inclined:* Here the belt conveyor conveys the material to a place situated above the feed point. The scale idler should be placed in the tail end at a point where the tension and variation of tension from no load to

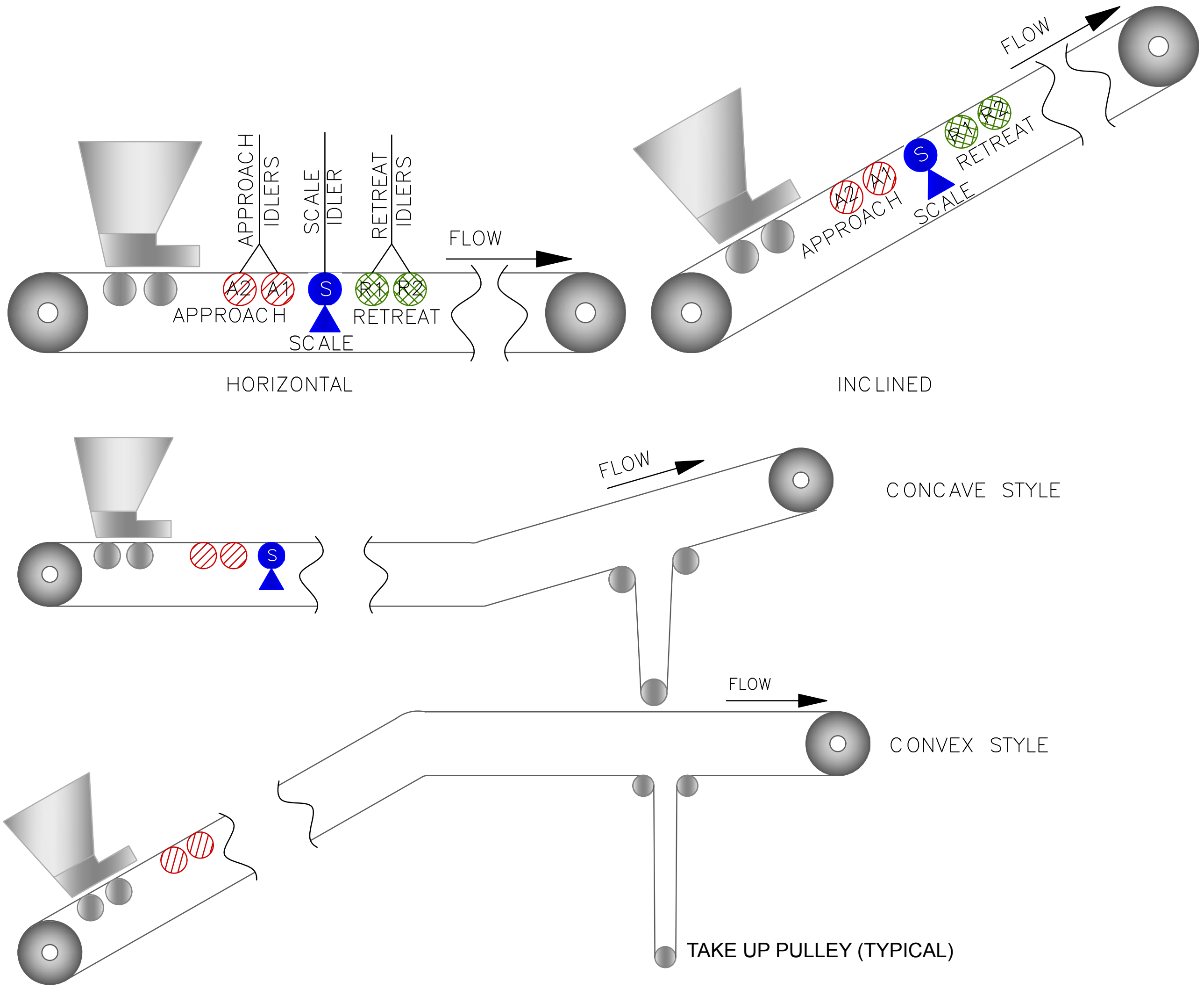


FIGURE VIII/4.2.1-1 Belt scale/belt weigher types and idler types.

full load is at a minimum, i.e., consistent tension. This is shown in Fig. VIII/4.1.2-2;

- *Concave and convex type:* There are difficulties in vertical curvatures. So, different configurations like concave and convex curvatures may be opted for. Also, concave and convex belt scale/belt weighers face difficulties in idler alignment, especially in the area of the curve. Concave and convex type belt scale/belt weighers are depicted in Fig. VIII/4.2.1-1. The concave curvature is more difficult to manage. It may lift an empty belt off the idlers around the curve, preventing a good empty belt zero balancing for the scale [27].

2. **Location of scale idler:** It is ideal to place the scale idler in the horizontal part of the belt section, but if the idlers are properly aligned, it is also possible to get a good result by placing scale idlers in the slope section also. In the case of a concave or convex curvature of the belt scale/belt weigher the scale idler can be placed at a minimum specified distance from the point of curvature. Normally such distances are 12 m on each side from the tangent point of curvature.
3. **Idler:** Idlers discussed in Subsection 4.1.2.8 are also applicable here, especially for the design standards referred to therein. The idler on which the load cell is placed is referred to as the scale idler. Adjacent to the scale idler two idlers upstream and downstream are referred to as approach idlers and retreat idlers, respectively.
4. **Belt take ups:** Belt take ups are mainly used for belt scale/belt weighers with a longer belt to adjust/control belt tension. Of the three basic types, i.e., screw, horizontal gravity, and vertical gravity, the vertical gravity take-up is the most reliable because it can react to changes in belt tension and maintain relatively uniform tension. Take ups are shown in Fig. VIII/4.2.1-1. Typical take up pulley shown. Take up pulleys may have take up gravity weight.
5. **Material loading:** There are various ways and means to feed the belt scale/belt weigher, feeding from other prefeeders the material loadings would be nonuniform, causing variations in belt tension and bringing about inaccuracies. Belt take ups can somewhat adjust the tension, but it is better to use gravitational feeding to get better material loading.
6. **Material feed point:** In some applications, conveying systems require multiple feed points, but these should be used at the same time. In the case of multiple feed points there can be variations in belt tension. Therefore, it is recommended to use a belt scale/belt weigher with a single feed point as far as possible.
7. **Belt sag and stiffness:** There should be specified sag and stiffness of the belt. Normally sag shall be around 2% of the idler spacing and the belt should be selected in such a way that it is not over-rated to avoid high stiffness, but should have the proper flexibility necessary for measurement.

4.2.3 SPECIFICATIONS OF BELT SCALE/BELT WEIGHERS

Specifications for a weigh feeder have been given in Table VIII/4.2.3-1. It is worth noting that as the specification is a general one, all the data will not necessarily match with any particular instrument chosen. Also, it has been attempted to put the best possible data from different manufacturers, and so there will naturally be a deviation from actual instruments. The specification given is just a guide and the reader should specify the requirements for a specific instrument bearing in mind the application in hand.

TABLE VIII/4.2.3-1 Specifications for Belt Scale/Belt Weigher

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Solid type	Chunky solids, or crushed solid ores/coal, clinker, grains, fine solids, flakes, etc., wide range of solid materials		

Continued

TABLE VIII/4.2.3-1 Specifications for Belt Scale/Belt Weigher—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
2	Feeding equipment	Wide varieties of hopper/bin of suitable design and/or silos with discharge valves		
3	Design/ambient temperature	Design: maximum 70°C; ambient: (–)20–60°C		
4	Typical capacity	As low as 0.1 t/h to 12000 t/h, depending on manufacturer and applications		As per manufacturer standard
5	Belt width	Typically 450–1400 mm		
6	Major components	Head pulley: rubber lagged Idler: CEMA standard; size, angle, application based (up to 35° trough angle) Scale idler: single/multiple (as per application) standard: CEMA. Refer to Subsections 4.2.1.2 and 4.2.1.3 Reducer: shaft mounted Belt: Endless polyester, vulcanized rubber, and other as mentioned in Section 4.1.2. Length as per application Frame: cantilever Belt load: dependent on material	To specify	
7	Materials of construction	Belt: Refer to Section 4.1.2 Frame: MS/CS/SS		
8	Sensing	Load sensor as per Section 4.3.0; speed sensing as per Section 4.4.0; integrator: as per Section 4.5.0		
9	Drive	Shaft mounted; AC/DC inverter motor		
10	Linear belt speed	2–4 (5) m/s standard		
11	Speed control	VFD major use		
12	Output	4–20 mADC, cumulative pulse frequency and smart version supports: Fieldbus communication (e.g., PROFIBUS/Foundation Fieldbus), some support bluetooth, PC interface, and standard links are available		
13	Output function	Rate flow, totalized flow, alarm, remote reset, zero adjustments, use in continuous process; batching functions		
14	Display and operator function	Digital display, operator reset, calibration, HMI support, adjustments and programming. Remote intelligent electronics cabinet and local control panel		
15	Electronics cabinet	Remote intelligent electronics cabinet and local control panel. Aluminum/MS different grades		
16	Power supply	Standard power supply 240/110 VAC 50/60 Hz/24 VDC		

Continued

TABLE VIII/4.2.3-1 Specifications for Belt Scale/Belt Weigher—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
Performance and Other General Details				
17	Accuracy	Overall 0.5% AR—1.0% AR standard; nonlinearity, hysteresis: <0.02% AR		
18	Reproducibility	0.02% AR		
19	Turndown	10:1		
20	Field calibration	Supplied with test load		
21	Accessories	Belt scrapper, zero speed, sway switch, etc. as required		
22	Special Feature	To specify — if any		

In this table mainly the mechanical parts of belt scale/belt weighers have been elaborated. Electronic components like weigh/speed sensors and integrator controls have been specified separately in Sections 4.3.0 through 4.5.0 to cover both weigh feeders and belt scale/belt weighers.

4.2.4 BELT SCALE/BELT WEIGHER SELECTION GUIDE

As there are many similarities between a weigh feeder and a belt scale/belt weigher, the selection guide indicated in Section 4.1.6 may be applied here also. However, in the case of a belt scale/belt weigher the accuracy requirement is not as important. Also, belt scale/belt weigher length can be much larger than that of a weigh feeder and it may have in-feed from various different kinds of equipment, e.g., from a reclaimer, etc. Essential requirements to be specified for selection of belt scale/belt weigher are described here:

1. **Application requirements:** For the selection of a belt scale/belt weigher the following system requirements should be specified or noted:
    - *Flow rate:* Maximum/minimum;
    - Particle size;
    - Material temperature;
    - Material bulk density;
    - Special material characteristics, such as abrasion, adhesion, causticity;
    - Accuracy required;
    - Intelligent electronics and associated interface;
    - Cost;
    - Type of in-feed;
    - Belt scale/belt weigher configuration;
    - Ease of installation and maintenance;
    - Technical support and services.
2. **Major selection criteria:** The following are major considerations:
    - Solid material class, e.g., bulk material, fruits, grain, etc.;
    - Industry type;
    - Whether a sanitary version is need;
    - In-feed type;
    - Idler loading (CEMA class);
    - Idler location;
    - *Scale idler (CEMA standard):* Single/multiple;
    - Belt tension;
    - Maximum belt speed;
    - Minimum/maximum loading;
    - Take up type;
    - Motor power requirement and sizing based on mechanical data with tolerance;
    - Shaft deflection and stress;
    - Sensor accuracy and effect on overall measurement;
    - Accuracy class;
    - Turndown ratio;
    - Approval requirements.

3. **General discussions:** Apart from these load cell types, sensing method and temperature compensation are also issues that need to be looked into. If the in-feed is from a reclaimer necessary modifications should be done to ensure that there are minimum tension variations in measurement. Test load and calibration issues are also important during selection.

   From the above discussions some knowledge of the electromechanical aspects of weigh feeders and belt scale/belt weighers have been gathered. However, such knowledge would not be complete unless details regarding load speed sensing, their regulation, and controls are properly conceived. In the following section these aspects will be concentrated on. As electronic control, i.e., speed control and variable energy drives for the motor, are only applicable to weigh feeders, these are discussed in the next section. The discussions begin with common electronics for both weigh feeders and belt scale/belt weighers.

4.3.0 Load Cell and Sensing Electronics

Both belt scale/belt weigher and weigh feeder operation depend on the performance of associated electronic sensors, monitor, and controls. *Load cells and associated electronics are not only used for belt scale/belt weighers but also in many other systems. The discussions put forward here for load cells are also applicable for other cases where load cells are used such as impact scale, hopper and platform loading*. An ideal load transducer should provide the following:

- Be very rugged and durable, without moving parts;
- Zero deflection;
- Extremely high resolution.

A simple strain gauge load cell with a modern analog-to-digital converter (ADC) is the best choice of load transducers available because of the following qualities:

- Robust construction without moving parts;
- Inherent low deflection;
- The shortest available stabilization time;
- Meaningful weight data;
- Nonsusceptibility to vibration;
- Availability of temperature and other compensations;
- Low-cost solution with modern high-resolution ADC to ignore dead weight.

1. **Load cell (LC) for weight measurement:** "Load cells" is often used as a synonym for a weight-measuring device. In reality this is incorrect, because load cells find their applications in other measurements also. Therefore, it is better to consider a load cell as a transducer, which produces an electrical signal proportional to the force applied. With this definition, pressure measurement is included as pressure multiplied by area gives force. Naturally, load cells can be hydraulic, pneumatic, or other types, such as strain gage, piezoelectric, and magneto-restrictive. In this part our main concern is to measure the weight for which strain gage types are commonly used on account of the following reasons:
   - Possible linear and precise measurement;
   - Simple bridge circuit for measurement;
   - Relatively smaller in size, easier installation and handling;
   - Smaller influence from temperature variation and can be compensated for;
   - No moving parts and longer service life;
   - Excellent fatigue characteristics [28];
   - Easy production;
   - Very high accuracy of 0.25% AR to 0.03% AR.
2. **Classification of load cells:** There are several types of load cells in industrial applications. We explore these one by one. In addition to those listed below there are other

classifications based on whether they are heavy duty, light duty, etc. There can also be classification based on the shape of spring materials, etc. The major classifications are listed here:

- *Loading direction:* Based on the direction of applied force on the load cell (LC) it can be a compression, tension, compression-tension (alternative), or bending type. These are shown in Fig. VIII/4.3.0-1.
- *Shape:* Based on the shape of the load cell it can be classified as beam type, S type, can type, washer type, compression style, etc. Some of these are also depicted in Fig. VIII/4.3.0-1.
- *Number of load cells application:* Based on the number of load cells deployed it can be classified as a single point load cell or a multipoint load cell, where the multipoint type is used when making a scale.

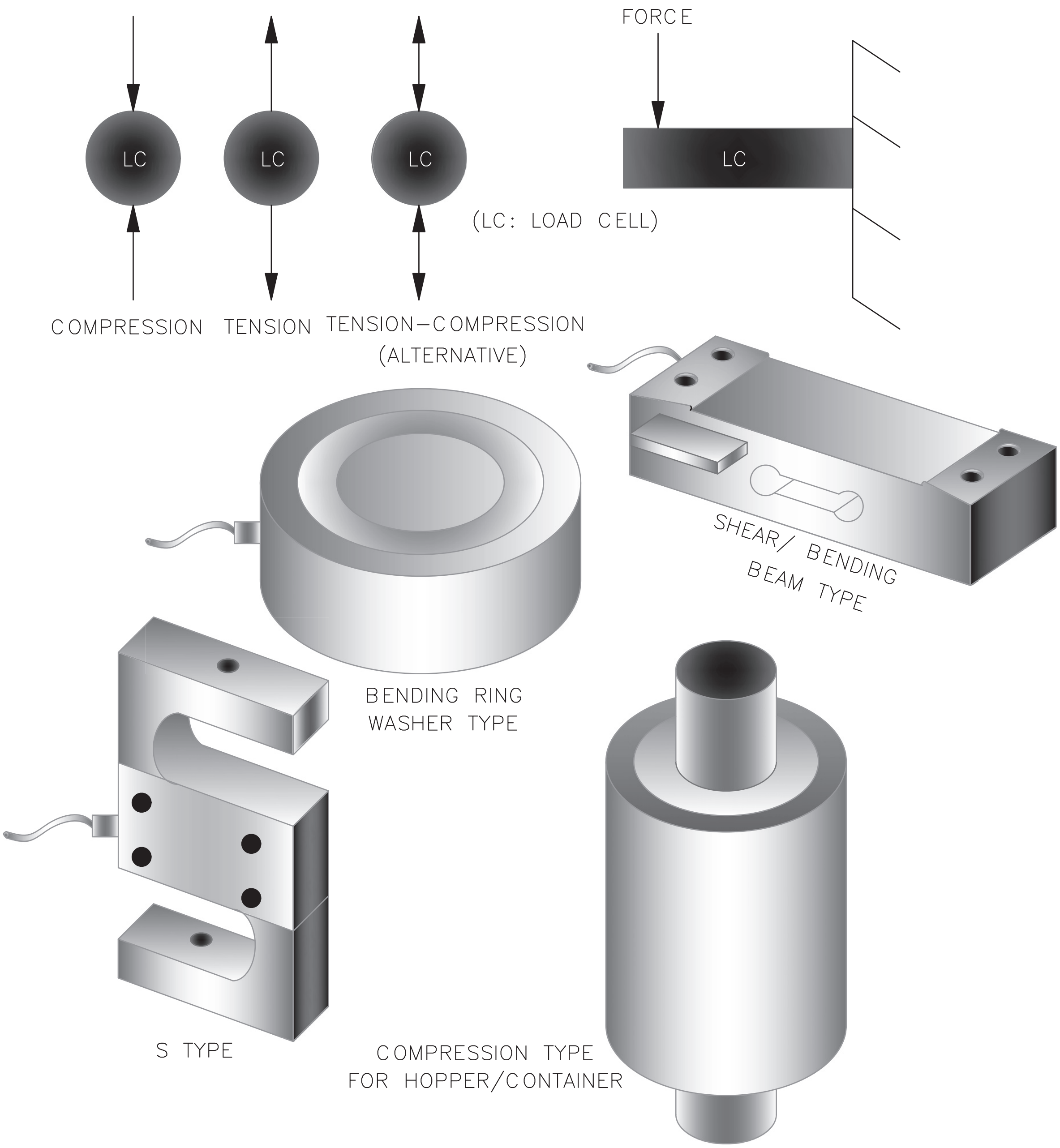


FIGURE VIII/4.3.0-1 Load cell types.

- *Air tightness:* In this type of classification, there are open type load cells, hermetically sealed load cells, and explosion-proof (flame-proof [2]) load cells.
- *Precision of measurement:* Based on precision of measurement it can be ultraprecision, precision, standard, or general-purpose.
- *Loading capacity:* Based on the loading capacity it can be classified as low capacity, mid range, and high capacity.

3. **Types of industrial load cells:** There are several types of industrial load cells and such classifications have been done combining the above properties with their usages. These are described here:
   - *Compression type:* Size around 50 mm diameter, compression type meant for high-capacity loads (0 up to 50,000 N) with minimum space occupancy. These are used for silo and weighbridge weighing. They find their use in test benches and industrial weighing. They are available in stainless rugged construction, with good accuracy and are available with NIST traceable calibration.
   - *Strain:* Used for both static and dynamic measurement. These are made up of fine-grade wire or foil with a grid, bonded in a matrix. The adhesive and carrier matrix also dissipate heat and insulate against electrical noise, which can act as interference and alter readings. The Wheatstone Bridge Circuit Theory is widely used in static strain measurement for its outstanding sensitivity [29].
   - *Beam:* Beam types can be of two types: shearing beam and bending beam. Medium-capacity load cells are available in SS and aluminum alloy, nickel plated, and CS. Typical capacity is 350 kg, but they are available in various capacities, including 50, 100, up to 1000 kg. Bending beams are used in platform scales, weighing small hoppers, belt weighers, weigh feeders, and other high-precision applications. The bending beam shows greater deflection and high strain at relatively low force. It exhibit excellent linearity. Shear beam load cells are suitable for all types of medium- and high-capacity weighing applications. Shear as a measuring principle offers good resistance against side loads and small sensitivity to the variation of loading position, this type also shows better overload capacity [30]. The shear type has a high capacity of around 5000 kg. They are available in heavy-duty shear beam applications. Shear beam and double beam load cells can be used in multiple cell applications, e.g., tank weighing. They are available with ex proof/ATEX certification also.
   - *Washer/pancake type:* This is a bending ring type load cell also known as a pancake type load cell. This is used mainly for silo/hopper weighing. The deflection of the load cell by the load is measured by the foil gage sensor, which is entirely sealed within a cavity inside the transducer [30]. The safe loading capacity is up to 750 kg.
   - *Platform (load pin):* These could be in hermetically sealed form for use in platform scale and small conveyors. They are available with a high accuracy of ±0.02% FSD, in resistive load cells built with bonded foil strain gages. On account of their ability for off-center compensation, they can measure accurately no matter where objects to be measured are placed on the loading platform [29]. Safe loading capacity is up to 1000 kg and they are used for filling/dosing machines.
   - *S-type:* These are beam type load cells. They are designed to provide the best performance in compact and versatile units. They are used for tension and pressure applications in suspended scales, tanks, hybrid scale and container weighing, i.e., hanging scale. They offer safe capacity up to 5000 kg and they adapt shear/bend beam measuring principles.
   - *Canister style:* Canister style load cells are available for compression and tension

loadings. They are used in single as well as multiweighing applications. These are rugged in construction and also available in stainless steel constructions. They are available in hermetically sealed and water-resistant enclosure. This type also finds its application in marine and submerged applications. All stainless steel construction is very reliable in harsh underwater conditions.

4.3.1 DESCRIPTIVE DETAILS OF LOAD CELL MEASUREMENT

Strain gages (SGs) in load cells can be of the foil type or semiconductor type. Strain gages are very suitable for single-, dual- and multiaxial SG measurements. The discussions start with the basic working principles of industrial load cells and by illustrating why various compensations are necessary and how these are implemented.

1. **Basic principle of measurement:** The load cell working on strain gage principles are utilized for industrial weighing purposes. The type of load cell may vary with the application of weight measurements such as for a conveyor, hopper, truck, etc., as discussed. However, in each case basically the changes in resistance of the strain gage on account of compressive, tensile, or bending forces are measured with the help of a bridge circuit, i.e., Whetstone's bridge. Fig. VIII/4.3.1-1 depicts such an arrangement for a bending type load cell.

   Load cells working on strain gage principle convert a mechanical force (i.e., weight) into an electrical signal and normally voltage changes due to a change in resistance for the applied force or weight. Specially formed electrical conductors, duly insulated by suitable insulating materials from the strain gages, which are attached to the load cell(s) by a specially formed spring body, by friction locking [31]. On account of the weight, i.e., force F as shown in Fig. VIII/4.3.1-1A, the spring body becomes deformed naturally, and as a consequence the strain gage also deforms elastically. Such changes in shape bring about the changes in resistance of the strain gages, as shown in Fig. VIII/4.3.1-1A, some strain gages are compressed while others become stretched as shown. So, on account of the changes in length, there will be changes in the resistance too, i.e., those which are stretched would have higher resistance, while other pairs will have lower resistance. For each load cell there will be at least ***four*** strain gages connected in such a manner that positive and negative resistances are added together [31]. This is done to get more imbalances in the bridge for measurement. It is interesting to look at the connections shown in Fig. VIII/4.3.1-1B, such that the stretched ones and compressed ones are in diagonally opposite sides. Here the bridge, like a normal Wheatstone bridge, between two opposite diagonal corners has a power supply applied and in the other pair of diagonal corners the signal is measured. The difference is that here a six-point measuring technique, i.e., change in sensor voltages, is also measured, so that with constant power supply, measured signal change is proportionate with changes in sensor voltage in the computing circuit.

   From the discussions above it is not clear *why at least **four** strain gages have been mentioned.* The answer to this lies with temperature compensation associated with the measurement. This will be discussed at length in the following subsection as it is a very important issue.

2. **Temperature compensation:** In order to understand the necessity for various compensations and the implementation of the same in the circuit it is necessary to have relook into the measuring circuit shown in Fig. VIII/4.3.1-1B. Therefore, we start the discussion from the beginning with a Wheatstone bridge with four resistances R1, R2, and R3 and the strain gage resistance at the fourth arm as shown in Fig. VIII/4.3.1-2A. When there is no stress on the stain gage the bridge circuit

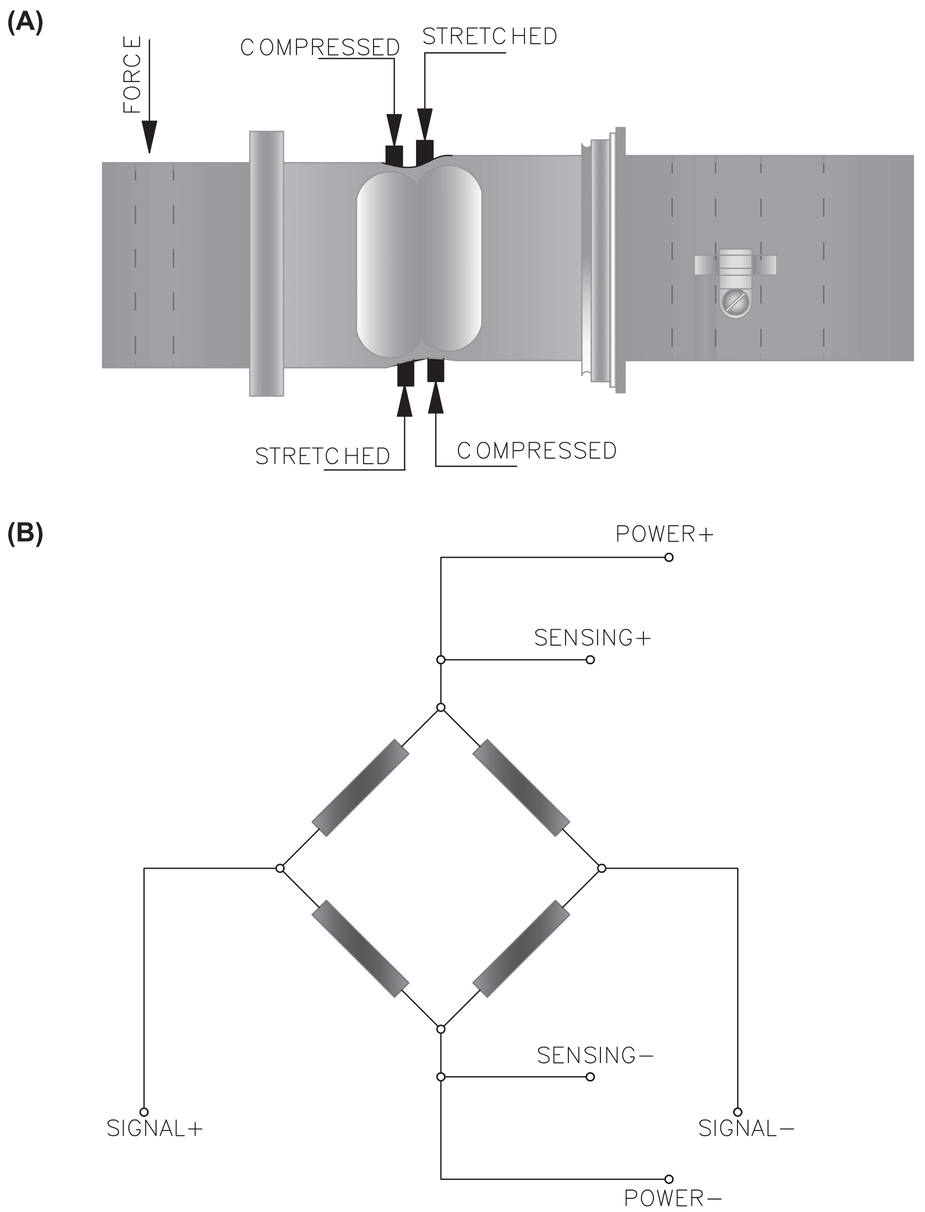


FIGURE VIII/4.3.1-1 Load cell measurement. (A) Bending load cell deformation sensing. (B) Bridge circuit for load cell measurement. *(B) Developed based on Load Cell, Siemens AG; Siemens Wt 10, 2010. http://www.automation.siemens.com/sc-static/catalogs/catalog/wt/WT10/en/WT10_en_kap03.pdf. Courtesy: Siemens.*

is in a fully balanced condition, i.e., no voltage/current signal between the output terminals (signal + and signal −), i.e. null balance.

When conductive metal is stretched, it will become longer and thinner, so, as per basic physics, the combined effect will result in an increase in the electrical resistance. Conversely, in the case of a compressive force (without buckling), the conductive metal is shortened and broadened. Therefore, as per basic physics, the combined effect will result in a decrease in electrical resistance. If these stresses are kept within the elastic limit of the metal strip (i.e., the conductive metallic strip does not permanently deform), the strip can be used as a measuring element for physical force. The amount of applied force, in this

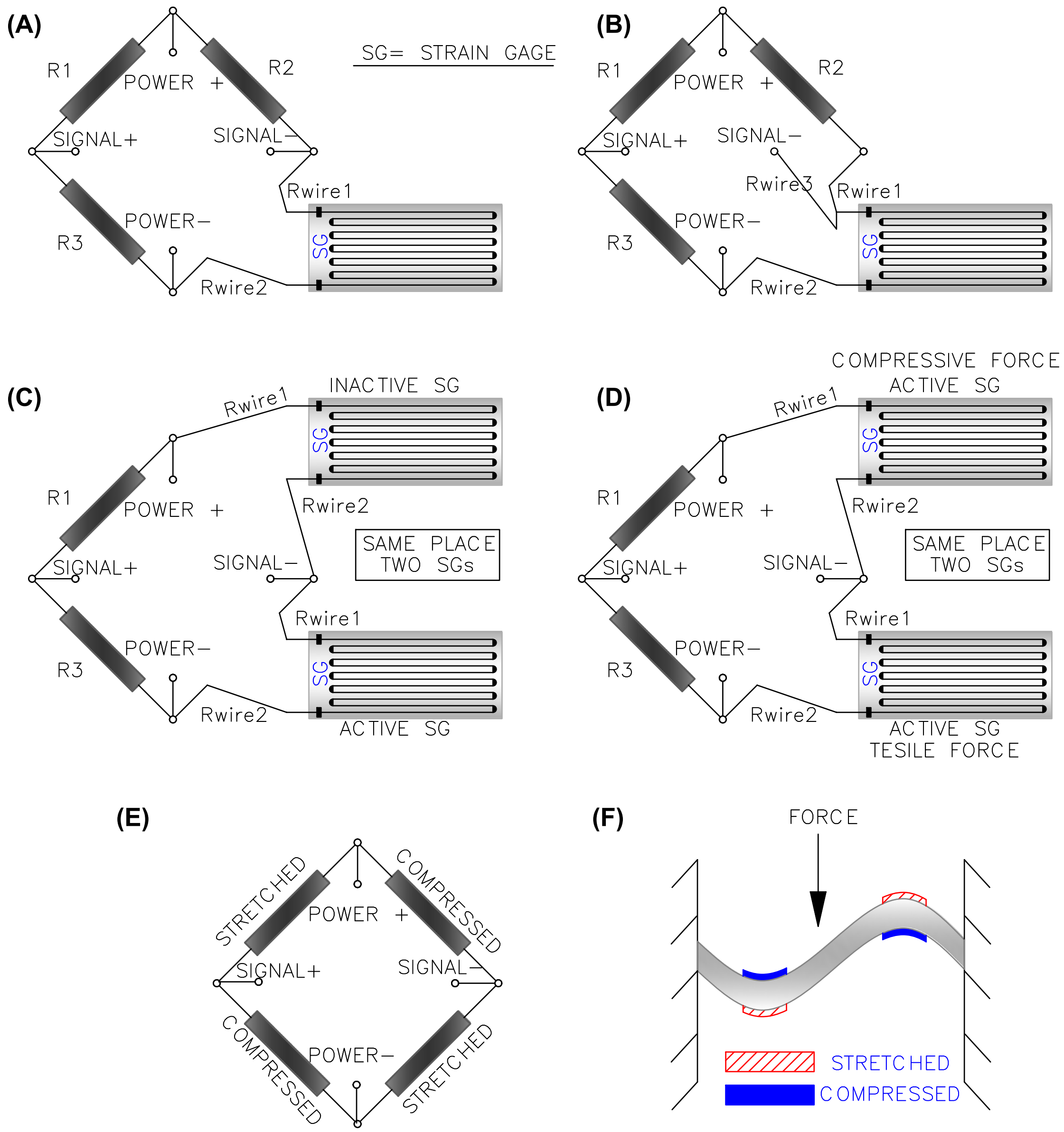


FIGURE VIII/4.3.1-2 Load cell measurement with compensation. (A) Quarter bridge W/O compensation. (B) Quarter bridge with wire compensation. (C) Quarter bridge with SG compensation. (D) Compensated half bridge SG. (E) Full bridge SG. (F) Weighing measurement.

case weight, can be inferred by measuring the resistance. Similar logic also holds good for semiconductor type strain gages also. Temperature is a vital parameter which affects many things, including the following:

- *Lead resistance:* There may be some distance between the measuring circuit in the panel and the strain gage located in the field, so these are connected by simple wiring. Based on variations in the ambient temperature there will be variations in these wire or lead resistances.
- *Change of elastic coefficient with temperature:* With changes in temperature, the

elastic coefficient of the spring material changes and affects the measurement, i.e., the output voltage of the measuring circuit, significantly. Typical values for ferrous metallic alloys and aluminum alloys are approximately −0.003%/°C and approximately −0.07%/°C, respectively.

- *Nonlinearity:* When a force is applied, the cross-sectional area of the spring material changes, and a linearity error will occur. Therefore some corrective linearity factor may be necessary.

We now look at these issues one by one. Lead resistance can be compensated easily by using three wires (as used in the case of three-wire RTD), shifting the signal measuring point to the field. Since the drop across the third wire is negligible with respect to the input impedance of the measuring circuit it can be neglected. This has been depicted in Fig. VIII/4.3.1-2B. This may be a good solution for RTD measurement but not for load cell weight measurement as it cannot take care of the other issues discussed above. This can be circumvented by using a "dummy" strain gage in place of R2, so that *both* elements of the ratio arm will change resistance in the same proportion when the temperature changes, thus canceling out the effects of temperature change. The "dummy" strain gage is isolated from all mechanical stress, and acts as a temperature compensation device. With temperature change, both gages will change in the same percentage, and the state of balance of the bridge will not be affected. Therefore, only a differential resistance produced by physical force can alter the balance of the bridge. This has been depicted in Fig. VIII/4.3.1-2C. This also suffers from nonlinearity, as discussed above. There will be an improvement in measurement when both strain gages are made active. These two strain gages may be exposed to opposite forces, e.g., the upper gage is compressed and the lower gage is stretched (i.e., tensile force). Opposite forces are considered, so that the bridge will be more responsive to the applied force. This is a half bridge configuration [32]. Referring to Fig. VIII/4.3.1-2F, it can be seen that when the force is applied in this method then there will be stretched conditions at two places shown by red hatches and compressed conditions shown by blue shade. Thus there can be two strain gages in compressed conditions and two in stretched conditions. Therefore, in place of two strain gages, four strain gages can be used in a bridge circuit as shown in Fig. VIII/4.3.1-2E as well as in Fig. VIII/4.3.1-1B. Thus the need for the use of ***four*** strain gages has been explained.

Now it is time to look into the specification of the load cell. It is worth noting that there are a variety of load cells, and it is difficult to specify all types, and so a general specification has been given.

4.3.2 LOAD CELL DISCUSSIONS

The load cell is a part of the weighing instruments which have a direct relation with legal trade regulations which can vary from country to country. There are also different classes of accuracy, etc. In order to understand and conceive the specification for load cell properly, it is necessary to understand the various terms used in load cell specification, mainly related to its capacity and various types of errors need to be considered while specifying a load cell. These are explored here.

1. **Legal trade standards for weighing and load cells:** Based on their overall performance capabilities, load cells and weighing instruments are ranked. A specific accuracy grade specifies an error envelope for certain parameters, such as linearity, hysteresis, temperature effects, creep, etc. [33]. Therefore, weight measurements, which are very much related to legal trade, have been categorized as per

mainly two legal trade standards in the world. It is recommended to refer legal trade standard for understanding. Highlights of these are:

- *United States (US):* In the US the legal standards for trade weighing instruments are laid down in handbook 44 of the National Institute of Standards and Technology (NIST). The evaluation of critical metrological equipment and components, including load cells, is formalized by the National Type Evaluation Program (NTEP). NTEP Class III covers most commercial weighing applications for systems with between 500 and 10,000 scale divisions. Class IIIL specifically covers larger-capacity applications to include vehicle, axle load, livestock, crane, and railway track scales as well as hopper scales (other than grain hoppers), which have between 2000 and 10,000 divisions [33]. Each class can be further subdivided into single and multiple weighing systems based on the usage of one or more load cells that are used in a particular system. The load cell error tolerance for **single and multiple systems are set at 0.7 and 1.0** times the scale divisions, *respectively.*
- *Europe and International:* As per the convention in Paris on October 12, 1955, an International Organization of Legal Metrology was set up and is known as the Organization internationale de metrologie legale (OIML). Recommendations and documents of this organization relate to specific measuring instruments and the technology is referred to as OIML R. OIML class III covers the commercial weighing applications between 500 and 10,000 divisions. The OIML does not recognize the difference between single and multiple cell applications, but it accepts and utilizes the concept in the apportionment of errors (OIML R76). Load cells are tested and certified according to OIML R60. The load cell error tolerance is set at 0.7 times the scale division—this is, for practical purposes, considered as the maximum permissible error.

2. **Performance and error details:** In this part various accuracy classes are defined and measurement errors are discussed. We start with the accuracy classes.
   - *Accuracy class:* A load cell is classified by alphabetical classification, i.e., classified by a letter A to D and the maximum number of load cell intervals stated in units of 1000.
   - *Load cell verification interval:* The load cell interval (v), expressed in units of mass, used in testing of the load cell for accuracy classification.
   - *Number of verification intervals:* The number of verification intervals (n), used in test of the load cell.
   - *Maximum permissible error:* Depending on the number of verification intervals for a load cell, it is divided into several classes defined by OIML. Most of the commercial measurements fall under class III. For a load cell in class C with a $p_{LC} = 0.7$ (OIML R60). The p_{LC} fraction (0.7 by default for all practical purposes) represents the apportionment error attributed to a load cell [30]. NTEP class III single falls in line with OIML; however, an additional tolerance step at 4000d is permissible for A5 compared to C5.
   - *Nonlinearity:* The deviation of the increasing load cell calibration curve from a straight line which passes through the minimum load output and the load cell output at the rated capacity at a stable ambient temperature 20°C.
   - *Hysteresis: This is as defined in Chapter I for other instruments.*

- *Creep:* The change in load cell output occurring with time while under constant load (>90% of capacity) and with all environmental conditions and other variables remaining constant. As per OIML R76, requires a 30-min test as shown in Fig. VIII/4.3.2-1B. As per NTEP, this is a 1-h test.
- *Minimum dead load output return (MDLOR) or:* The difference in load cell output at minimum dead load, measured before and after a 30-min load application of at least 90% of the cell's rated capacity (OIML only). This has been depicted in Fig. VIII/4.3.2-1C.
- *Temperature effect on minimum dead load output:* The change in minimum dead load output due to a change in ambient temperature.
- *Temperature effect on sensitivity:* The change in sensitivity due to a change in ambient temperature as shown in Fig. VIII/4.3.2-1C.

3. **Load cell capacity:** It is important to understand how the capacity of load cell is arrived at. There are a number of factors, as shown in Fig. VIII/4.3.2-1A, that are responsible for defining the capacity of a load cell.
   - *Minimum (dead) load:* This refers to the minimum force or weight to be applied to

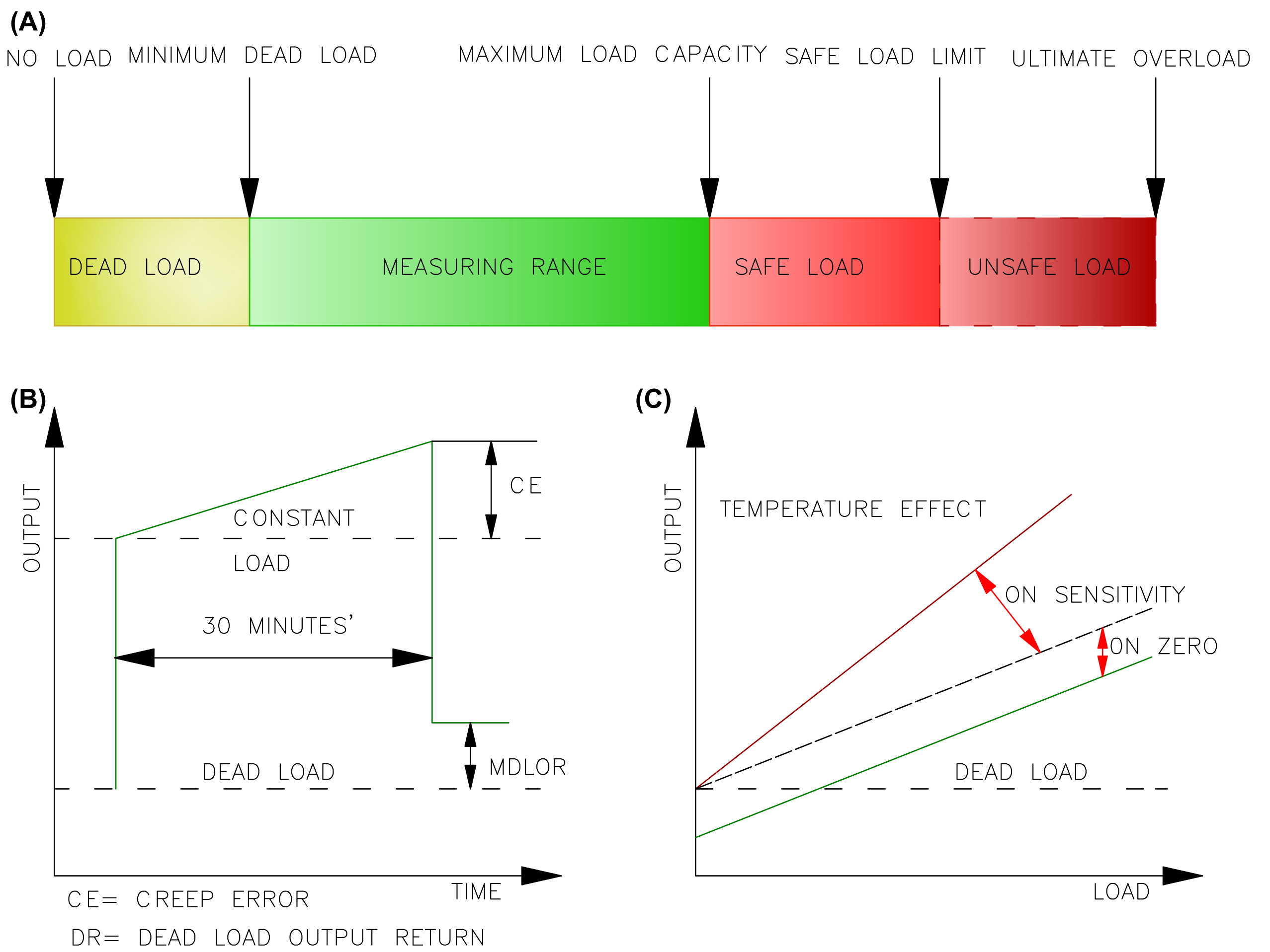


FIGURE VIII/4.3.2-1 Capacity and measurement errors for LC. (A) Load cell (LC) Capacity details. (B) LC error types. (C) Temperature effect.

a load cell without exceeding the maximum permissible error (MPE) discussed below. (This is specified as *Emax*/γ, where *Emax* represents the load cell's rated capacity and γ represents a value which is specified by the load cell supplier.)

- *Maximum capacity:* This refers to the largest force or weight to be applied to a load cell without exceeding the MPE defined below.
- *Load cell measuring range:* This represents the difference between the maximum capacity and minimum (dead) load defined above.
- *Capacity rating:* This is the maximum load which may be applied to obtain an output voltage equal to the rated sensitivity. This load is often equal to maximum capacity
- *Safe load limit:* A load cell can withstand more load than that defined by maximum capacity. It gives the maximum load that can be applied without producing a permanent deformation and/or shift in the performance characteristics.
- *Ultimate overload:* The maximum load that can be applied without permanent deformation of the load cell.

4.3.3 LOAD CELL SPECIFICATION

The specification for a weigh feeder has been given in Table VIII/4.3.3-2. The specification given is just a guide and the reader should specify the requirements with due modification based on the intended application.

Since the load cell considered here is not only meant for belt scale/belt weighers or weigh feeders and other solid flow measurements but for other systems also, a general specification for different types has been given in tabular form. Performance data are in line with legal trade systems discussed in Section 4.3.2.

(*Table VIII/4.3.3-1 gives abbreviations and application column abbreviations used in the load cell specification in Table VIII/4.3.3-2.*)

From the discussions it is shown that two distinct standards, H44 and R76, facilitate the achievement of measurement credibility. Only the approach roads are different. The objective of H44 is to eliminate those devices that give false readings, while the major objective of R76 is to evaluate an instrument's characteristics in a uniform and traceable way. With this the discussion on load cells comes to an end and we now explore speed sensing for belt scale/belt weighers and weigh feeders.

TABLE VIII/4.3.3-1 Abbreviations Used in Load Cell Specification

Symbol	Detailed Meaning	Symbol	Detailed Meaning	Application (Col.) Symbols	
AC	Accuracy class	LVI	(max/min) Load verification interval	CH	Container/hopper/tank
APP	Application	Mat	Material	COS	Conveyor scale
BL	Break load	SL	Safe load	PS	Platform scale
CR	Capacity rating	SV	Supply voltage	R	Rail
Ex	ATEX rating	TR	Temperature range (operating)	V	Vehicle/truck
IP	Degree of protection				

TABLE VIII/4.3.3-2 Specifications for Load Cell

Type	App	AC	CR (Kg)	SL %	BL %	LVI		TR (°C)	MAT	IP	SV (DC)	Ex**	Remarks
						Max	Min						
Platform	PS,COS	C3[a]	3–100	150	300	3000[a]	15,000	(–)10–65	SS, Al	65	12	Yes	As below
Bending beam	CH, COS	C3,4,5[a]	10–500	150	300	3000[a]	15,000	(–)30–65	SS, AL	68	10–15	Yes	**Various groups
Shear beam	CH, COS	C3,4,5[a]	10–5000	150	300	3000[a]	10,000	(–)30–65	SS	67	10–15	Yes	As above
Pancake	PS,CH, COS	C3	60–60000	200	500	3000[a]	17,500	(–)30–70	SS	67	10–30	Yes	
S Type	CH,SS#	C3	10–10000	150	300	3000[a]	12,000	(–)30–65	SS	67	10–15	Yes	SS# sus-pended scale
Compression cell	CH,R,V	C3	500–300000	150	300	3000	25,000	(–)30–65	SS	67	10–15	Yes	

[a]*Cn, n × 1000, i.e., C3: 3000; normal creep error: ≤±0.02% FSD; Temperature: sensitivity: ∼0.014% FDS/5K and Temperaure: zero error: 0.017% FSD/5K.*

4.4.0 Speed Sensor and Sensing Electronics

From the discussions on load cell it has been illustrated that the accuracy of load cells is very precise, however when they are installed in a conveyor the accuracy falls for many reasons (typically accuracy of 0.25% AR−0.5% AR is common for belt scale/belt weighers or weigh feeders). Since the feed rate in a belt scale/belt weigher or weigh feeder is computed by multiplying the load signal with the speed signal, it is imperative that signals from speed sensors play a key role in any feed rate measuring system—the overall system accuracy depends on a consistent speed signal. *Speed sensors and associated electronics are not only used for belt scale/belt weighers but in many other systems also. The discussions put forward here for speed sensors and associated electronics are also applicable for all cases where speed sensors and associated electronics are used.* If the accuracy of speed measurement is not precise then the accuracy of feed rate measurement will deteriorate. Therefore, it is necessary that the tachometer should have a high resolution, i.e., high numbers of pulse/revolution (e.g., >500); this is especially true for low belt speed. There are many schools of thought for placement of the speed sensor in the conveyor. Many manufacturers are of the opinion that on account of dirt it is better to avoid the tail end pulley as the mounting location for a speed sensor. The speed along the length of the belt is not same, so it is necessary to measure the speed at a suitable place. Modern speed sensors are used with encoders. Speed sensors with encoders should not be mounted on the head pulley as there is a greater chances of slippage there. Therefore even if there is dirt, it is always preferred to mount the speed sensor at the tail pulley to get the benefit of the fundamental sensing capability. This is the best location for sensing material speed because the belt makes a 180 degrees wrap around the tail pulley, ensuring maximum belt friction and minimal slippage. Therefore, the tail pulley only moves with the belt and material. Tension rolls, if used, are more susceptible to slippage for speed sensing. We now concentrate on the descriptive details of speed sensing.

4.4.1 DESCRIPTIVE DETAILS OF SPEED SENSING

1. **Measurement requirements:** A simple tachometer mounted directly onto the speed source is the best choice for speed sensing in a belt scale/belt weigher or weigh feeder. Modern digital or optical encoders are the most common tachometers used to measure the travel of the belt. It goes without saying that the higher the resolution, the smaller the belt increment that can be measured and the better will be the measurement performance because speed measurement is very critical in feed rate measurement in belt scale/belt weighers or weigh feeders. Present-day encoders can produce a pulse per 1 mm belt travel. In order to cater to harsh feeding environments, modern encoder electronics are available in a suitable enclosure of required IP ratings. However there are cases where the return belt is used for measurement. A few types, including one on a return belt have been depicted in Figs. VIII/4.4.1-1 and associated encoder details are available in VIII/4.4.1-2.
2. **Speed sensing:** In modern speed-sensing (digital) tachometers, encoders are utilized. A high-resolution speed sensor provides signal pulses whose frequency is proportional to the shaft speed. Therefore, by pulse counting the shaft speed is determined accurately. Therefore, a (digital) speed-sensing tachometer converts the shaft rotation into a pulse train of 256, 500, 1000, or 2000 pulses per revolution using a high-precision rotary encoder. There are basically two kinds of encoders used, one is optical and the other is magnetic. The magnetic type may be of different kinds, such as proximity switch or Hall effect.
3. **Optical encoder:** Basically, this type rotary optical encoder uses a sensor to identify a position change when light passes through a patterned encoder (optical shift type) wheel or disk. Major parts of the rotary optical

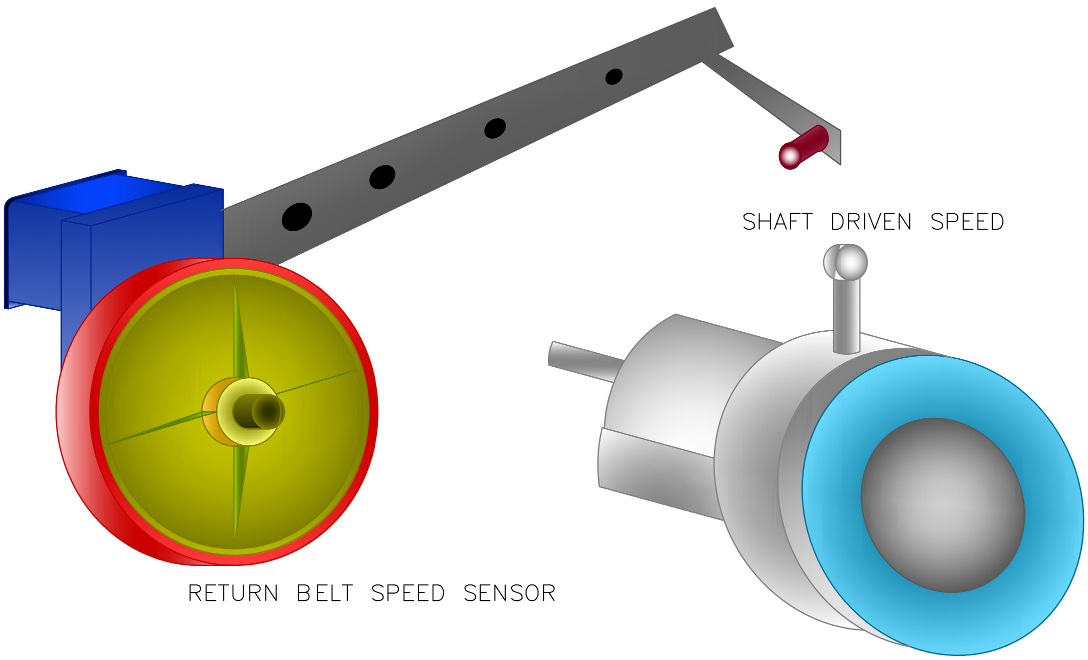


FIGURE VIII/4.4.1-1 Speed sensor.

Encoder: *An encoder is a kind of sensor for mechanical movement, to generate digital/pulse signals in response to mechanical motion. The encoder provides the user with the information about the position, speed and direction about the mechanical movement of the equipment for which the encoder has been deployed. The encoder could be linear type (responds to motion along a path) or rotary type (responds to rotational motion – in our belt feeder it is rotational motion). Encoders are categorized as* incremental type *(that generates pulse train to get information about position and speed) and* absolute type *encoders (that generates unique bits corresponding to position). In practical use, there may be single and /or two (viz. quadrature) or more encoders in use. Encoding for rotational speed can be done by optical method or magnetic method (proximity type or hall effect type).*

FIGURE VIII/4.4.1-2 Encoder.

encoder are: LED light source, photo-detecting receiver/sensor, and movable disk. The LED shines through one side of the optical encoder. The encoder wheel or disk has a series of tracks opening on it. As the disk moves, it breaks the encoder light. The detecting sensor on the other side detects the same and produces output pulse proportional to the speed of the shaft as the disk is mounted on it. The code disks (also called wheels) on rotary optical encoders consist of etched metal, Mylar, emulsion on tempered glass, or chrome on glass. In the case of the optical shift type, there will be a mask and the detector changes the open/close pattern. However, this is a basic operation in its simplified version for speed measurement.

4. **Magnetic encoder:** In the magnetic type encoder a small gear rotates with the shaft near a proximity switch, as the gear teeth pass the proximity switch generates a pulse output proportional to the speed of the shaft.

Alternatively, a rotor fixed on the shaft contains alternating evenly spaced north and south poles around its circumference and as the shaft rotates, the sensor on the other side detects these small shifts in position $N \gg S$ and $S \gg N$. Hall effect and magnetoresistive are the two methods that can be used to detect the changes. Hall effect sensors work by detecting a change in voltage by the magnetic deflection of electrons detailed out in chapter X. Magnetoresistive sensors detect a change in resistance caused by a magnetic field.

5. **Discussions:** Magnetic encoders have an edge over optical encoders. This is because of the entry of contaminants through seal failures, which can deteriorate optical encoder performance.

   The optical disk may shatter during vibration or impact.

4.4.2 SPECIFICATION OF SPEED SENSING

A brief generalized specification of a speed sensor along with an encoder has been presented in Table VIII/4.4.2-1. The data presented here are data from reputed manufacturers and as different data are available from various manufacturers, the best possible data have been selected, and so they may not match with any particular manufacturer. The reader is requested to use the data sheet as a base document and, based on the intended application, the most suitable one should be chosen in consultation with the manufacturer.

With this the discussion on speed sensing comes to an end. We now investigate details about electronic integration and control systems along with their communication systems.

TABLE VIII/4.4.2-1 Specifications for Speed Sensor With Encoders

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Sensing principle	Digital tachometer with encoder to produce pulse for shaft rotation		
2	Resolution	High-resolution pulses		
3	Input	Shaft rotation 0.5 to >2000 RPM		
4	Ambient temperature	−40 to 80°C		
5	Humidity	98%		
6	Shock and vibration	50 g (10 ms)/20 g (5—2000 Hz)		
7	Starting/running toque	Manufacturer's standard		2.5 Ncm (typical)
8	Encoder type	Incremental (2 ch)		
9	Frequency response	>200 KHz		
10	Quadrature	90 ± 22 degrees, normally CCW leading		
11	Enclosure	NEMA 4X/IP66		
12	Material	Painted aluminum/stainless steel		

Continued

TABLE VIII/4.4.2-1 Specifications for Speed Sensor With Encoders—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
13	Output	Open collector/10–30 VDC Pulse: 256/500/1000/2000 pulses per revolution Frequency: 2–2000 Hz or more		
14	Output function	Belt speed for weigh feeder rate computation		
15	Ex-proof	ATEX rating		
16	Power supply	24 VDC 10–30 VDC		
17	Special feature	To specify – if any		

4.5.0 Electronic Integration and Control Systems

There are two sets of signals, one each from the weigh scale and speed sensors, which need to be multiplied and integrated for computation of feed rate. Also, for a weigh feeder there should be a controller to control the speed of the driving motor for the weigh feeder. In this brief discussion electronic integration and control systems shall be presented on. The discussion starts with functional details of the above system.

4.5.1 FUNCTIONAL DETAILS OF WEIGHING ELECTRONIC INTEGRATOR AND CONTROLLER

When used with Belt scale/weigher of weigh feeder, the name suggests its main function is to integrate the feed rate with time. However in reality it performs two fold functions. One of the function of this unit is to compute feed rate taking signals from load cell and speed sensor as detailed out earlier (i.e. to act as multiplier/signal processing unit). The other function is to integrate the feed rate with time. Integrators are also these in designed for easy-to-read displays with straightforward operation and calibration through keyboards or touch screens and software that allows step-by-step set-up and operational procedures. All data and user instructions are displayed on a bright alphanumeric display of different kinds such as LED, LCD, and vacuum-fluorescent. These intelligent operator interfaces (displays, keyboard, or touch screen, etc.) are used for all interfacing and data entry. Also these integrators for belt scale/weigher and weigh feeders are designed to accept the required analog/digital I/Os as well as with external communication facilities to interface the external control and monitoring needs of the plant. Various I/Os mentioned above may be necessary for process control interfaces (i.e., a process interlock) and also for basic protection of a belt scale/belt weigher or weigh feeder (i.e., interlock from zero speed switch, sway switch). It is worth noting that many reputed manufacturers also offer similar programmable electronics not only for belt scale/belt or weigher feeder applications alone, but that may be used for their other solid-measuring systems, such as impact scale, loss-in-weight feeder, check weighers, etc., e.g., the Ramsey 2000 series electronics can be used for many solid flow-metering devices. This means that the details given here can be used for programmable electronics of other solid flow-measuring systems as well. In the case of a weigh feeder the feed rate can be set and controlled with a variable-speed drive connected to the weigh feeder. Therefore, in the case of a weigh feeder, in addition to the electronic integrator discussed above, there should be a controller at least with PID operation to get the set flow through the weigh feeder. As a corollary to this it transpires that in the

case of a weigh feeder there should be one controller and associated interfaces with external control systems such as PLC/DCS. At times it is possible that a number of weigh feeders or belt scale/belt weighers are integrated through a common control, which is not uncommon in steel plants where slightly bigger control systems incorporating PLC may be adapted. This is stated here to indicate that there can be wide varieties of integration and control electronics. Therefore, only the systems are discussed in general terms, which not only can vary with manufacturers but also with applications. Therefore, the following basic functions are expected of electronic integration and control systems:

1. Acceptance of weigh scale signal from load cell and speed signal from speed sensor;
2. Computation of feed rate from above signals and integrate over specified time;
3. Integration/totalizing feed rate signal to produce totalized flow;
4. Handle interlock and protection and external I/Os;
5. Generation alarms and alarms management;
6. Display of primary signals like load and speed values, feed rate signal, and totalized flow;
7. Operator interface (e.g., reset);
8. Communication and interfacing with other systems;
9. Feed rate control (for weigh feeder);
10. Speed control and control interface for drive motor (for weigh feeder).

We now look into the details of various features offered by different manufacturers, so that the reader will be in a position to select the feature best suited for their intended application.

4.5.2 FEATURES AVAILABLE FOR WEIGHING ELECTRONIC INTEGRATORS AND CONTROLLERS

There are wide varieties of advanced features now available from various electronic integrators and controllers for weighing systems available in the market. A few such features are listed below to enable the reader to choose the most suitable for the intended application. It is worth noting that all these features may not be available for a single product. Also, it may be possible that selected feature combinations are not feasible for any vendor, in which case the reader needs to assign the priorities for the application and select the vendor accordingly. Some of the features include but are not limited to the following:

- Multilingual system possible;
- Legal trade standards possible;
- High-precision ADC with 16 (common)/32 bit processing and controls;
- Performance parameters as per applicable legal trade standard;
- Common operation, set-up, and calibration for all weighing applications for better familiarization;
- Digital electronics with accurate, drift-free performance;
- Synchronization of prefeeding devices/equipment;
- Easy autozeroing and tracking of the same for empty operation of conveyor;
- Autocalibration and span method for electronic calibration standard with different test load forms;
- Operator-selectable time for autoreminders for recalibration timing;
- Suitable linearization for a wide range of operations for better measurement accuracy;
- Number of programmable features for customization of integrator and controller;
- Selectable outputs from menu and output types;
- Selectable output display types;
- Different types of displays including color, high-resolution LED monitor, and optional printers;
- Five to six digit totalizing (resettable) in different units;
- Selectable delay in time or length of belt travel for better control;
- Wide choice of selectable and programmable outputs and output types;

- Selection of a wide range of communication facilities;
- Support for different links, interfaces, protocols, and fieldbus systems;
- Independent and programmable delay in output and display;
- Facilities for incline compensation and moisture compensation;
- Refill, deviation, and other alarm management (as applicable);
- Surge and other applicable protection and interlocks;
- High electromagnetic compatibility;
- Optical/galvanic isolations;
- Suitable enclosure for harsh environmental conditions with suitable materials;
- Integrated diagnostic and self-test functions;
- Possible for ATEX certification and use of IS circuit;
- Power fail-safe data storage possible;
- Event logging-span, alarm, zero, and data change events logged;
- Audit trail (trade certification approved);
- Status, event, adjustment, and quantity protocols;
- Simulation operation for test and learning purposes possible;
- Back lash controls;
- Remote control set point for control;
- Batch quantity feed controls/dosing controls;
- Fuzzy logic controls for dosing conveyors.

4.5.3 DESCRIPTIVE DETAILS OF WEIGHING ELECTRONIC INTEGRATORS AND CONTROLLERS

Modern weighing equipment must be capable of interfacing with a variety of peripheral equipment for monitoring, supervisory control, and data acquisition purposes. To accommodate these needs, extraordinary communication capabilities are necessary for interfacing with peripheral equipment, control systems, and networking systems. Also, operational flexibility is provided by programmable features in weighing electronics. Typical Belt feeder integrator and control has been depicted in Fig. VIII/4.5.3-1.

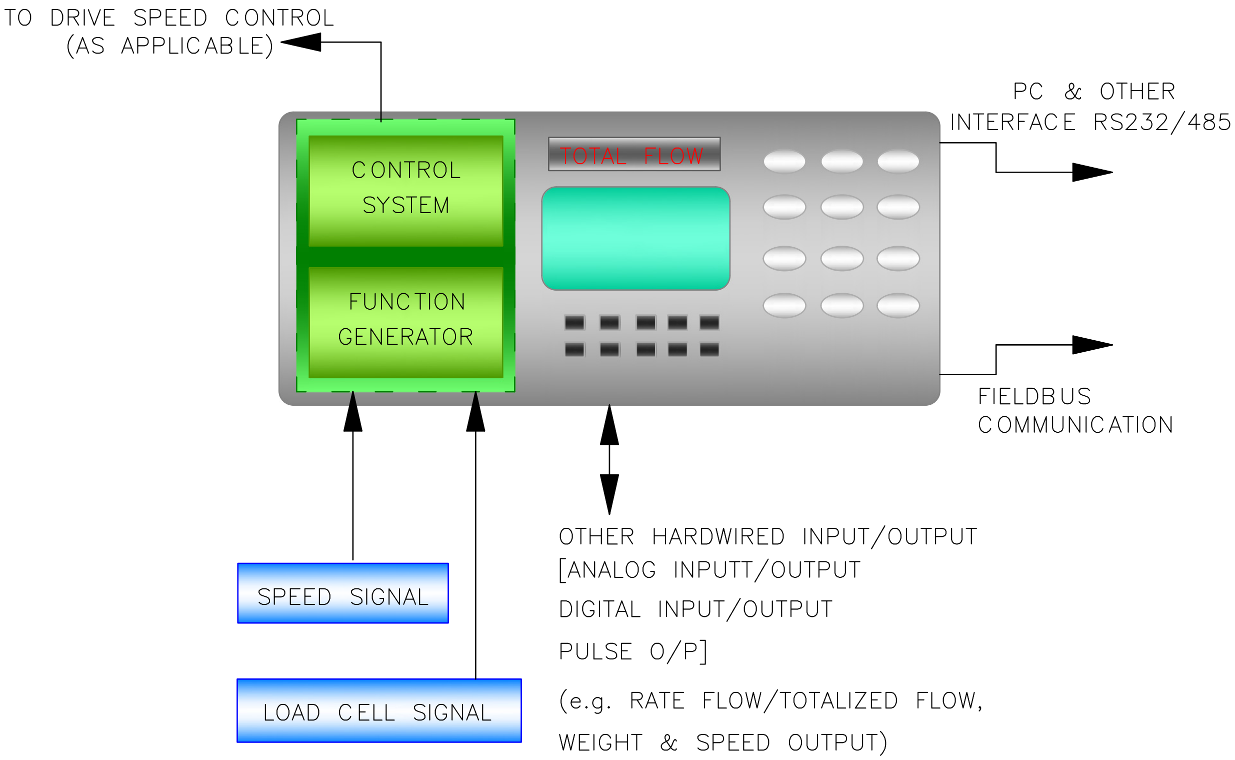


FIGURE VIII/4.5.3-1 Belt feeder integrator and controller.

1. **Basic integrator and controller:** The weighing electronic integrator and controls system receives a signal from the weigh scale and speed sensor(s). Using a combination of high-resolution electronics and intelligent filtering with computational techniques, it is possible for the electronic integrator to continuously calculate the feed rate and totalized feed. From this calculation, the intelligent electronic controller utilizes a sophisticated software algorithm to produce the required controlled output to regulate the speed of the weigh feeder driving motor with help of a suitable interface with a motor speed controller. The computer (which can be embedded a microcontroller) would operate as per the customer program and desired set points (especially for the weigh feeder controller) besides being connected to external control systems, such as DCS/PLC through proper RS links, field, and other communication bus or network systems.
2. **Basic displays and operator interface:** The displays of integrators normally include but are not limited to:
   - Feed rate;
   - Totalized weight;
   - Belt load;
   - Belt speed;
   - Feed rate set point (weigh feeder);
   - Feeder control output (weigh feeder);
   - Alarm relay and management;
   - Set point;
   - Manual/auto mode;
   - Raise/lower.

   These displays could be bright LEDs and or LED/TFT monitors and associated keyboards and touch screen. There are several varieties available from different manufacturers.
3. **Interfaces and communications:** The integration of various systems is currently popular because with this it is possible to save space and reduce the training period for operators when common types of displays and operators' interfaces are called for. Also, with this it is possible to take the benefit of use of common control systems, which otherwise would have been too costly. With digital communications it is possible to connect field instruments to the main control system, such as DCS/PLC. The majority of electronic integrators and control systems are available with the following additions:
   - Standard built-in Modbus RTU slave or ASCII slave via RS-links, namely, RS 232/485;
   - Miscellaneous networks, such DEVICE NET, Ethernet/IP, MODBUS/TCP, CONTROL NET;
   - Field bus: Profibus DP, Profinet, Foundation fieldbus;
   - Standard supportive I/Os and encoders (e.g., Allen−Bradley Remote I/O);
   - Interface for PC master control for PC-based systems with necessary links and protocol;
   - These are a few examples of available options.
4. **Other Miscellaneous controls and programs:** In weigh feeding control a number of other control systems are needed, such as:
   - *Blending of multiple materials:* Material blending with multiple weigh feeders;
   - *Preset flow control:* Preset flow control for batch and dosing controls with configurable dead range and automatic zeroing;
   - *Program setting and diagnosis:* Windows-based programs for easing out parameter setting and use of diagnostic tools, e.g., EasyServe PC program.

4.5.4 SPECIFICATION OF WEIGHING ELECTRONIC INTEGRATORS AND CONTROL SYSTEMS

A brief generalized specification of a weighing electronic integrator and control system has been presented in Table VIII/4.5.4-1. The data presented here are data from reputed manufacturers and are available from various manufacturers, with the best possible data having been selected,

and so it may not match with any particular manufacturer. The reader is recommended to use the data sheet as a base document and, based on the intended application, choose the most suitable in consultation with the manufacturer.

After the discussion on the integrator and controller we now look into details of the motor control system.

4.6.0 Motor Speed Control

The drive for a weigh feeder can be either a DC motor or an AC induction motor. Speed control of DC drives is a comparatively easy proposition but these are less common nowadays. In the majority of cases, an AC motor with drive controls is used for weigh feeders. Two methods, variable-voltage

TABLE VIII/4.5.4-1 Specifications for Electronic Integrator and Control System

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Application	Integration and computation of feed rate, totalizing flow, control of weigh feeder batch, and other controls		
2	Operating temperature	−20 to 60°C		
3	Storage temperature	−30 to 70°C		
4	Enclosure type	NEMA 4X IP66		
5	Analog input type	4/0−20 mADC/0−10 VDC		
6	Analog output type	4/0−20 mADC/0−10 VDC		
7	Binary input/ output	Potential free contact NO/NC For interlock and alarm		
8	Contact rating	Suitable rating around 3 A at 240 VAC or 0.3 A at 30 VDC		
9	Alarm management	Yes		
10	Impulse input	Totalizing counter		
11	Isolation	Galvanic/optical isolation for I/Os		
12	Power supply	110/240 VAC 50/60 Hz or 24 VDC		
13	Display type	LED (LCD also), vacuum fluorescent, TFT/LED monitor		
14	Display output	Rate. Totalized, belt load and speed, control set and others		
15	Features	Auto zeroing, calibration, etc.; refer to Section 4.5.2		
16	Serial interface	Printer, large displays, other software systems		
17	Communication	Fieldbus, Ethernet/IP, RTU MODBUS		
18	Communication protocol	MODBUS RTU		
19	Special feature	To specify − if any		

variable-frequency drive (VVVFD) control and variable-frequency drive (VFD) controls are commonly used methods for AC motor control.

AC drive control: Assume that the voltage applied to a three-phase induction motor is sinusoidal and neglect the voltage drop across the stator impedance. Then we have at steady state

$$V = kj\omega\varnothing \qquad \text{(VIII/4.6.0-1)}$$

where V = voltage; k = proportionality constant; ω = angular frequency; and Ø = stator flux. Thus we can see that if the stator impedance is ignored, the torque remains constant and is independent of supply frequency and voltage if V/f remains constant. In this connection, Fig. VIII/4.6.0-1B may be referenced.

When the voltage is low, the frequency is low and stator impedance cannot be ignored. Another issue is that at low speed there will be more flux in the air gap, and so core loss will be greater in VFD. For VVVF, faster power switching through power transistors/IGBT gives better results. However, in the case of a weigh feeder, since constant torque requirement is not mandatory, VFDs for speed controls are well suited and have become popular. Let us now concentrate on the motor speed control by variable-frequency drive (VFD).

Variable-frequency drive control: Fig. VIII/4.6.0-1A illustrates the basic building block for a VFD. AC motor speed (S) is given by:

$$S = \frac{120f}{P} \qquad \text{(VIII/4.6.0-2)}$$

where f stands for frequency of the supply, and P is the number of poles. Of the two parameters responsible for motor speed, P is not changed as it calls for physical change in the motor and rewinding, but it is easier to change the frequency of supply. As long as the f/P ratio is maintained, the rated torque can be developed. This indicates that whenever the speed of an induction motor is controlled, both by frequencies as well as voltage, one would have a different torque, as shown in Fig. VIII/4.6.0-1B. This ratio is varied in input, which consists of an isolation transformer, a rectifier circuit, and a DC bus section

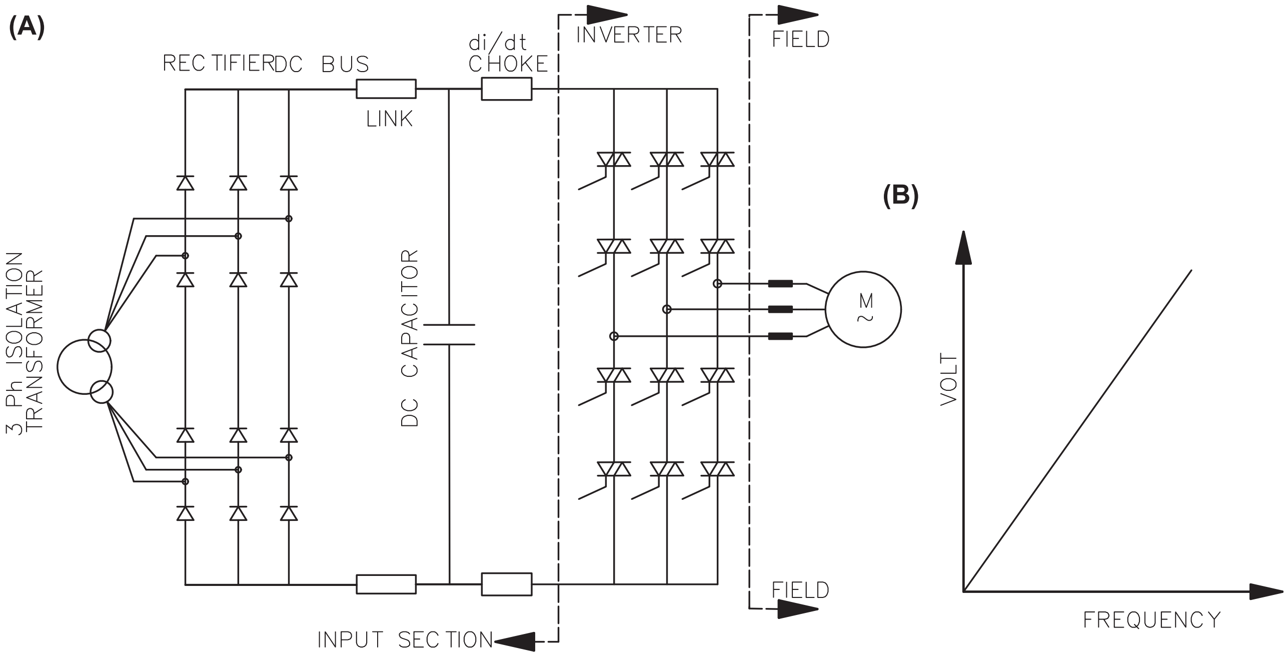


FIGURE VIII/4.6.0-1 Variable-frequency drive control. (A) Basic building block for VFD. (B) Torque development. *Taken from the author's book: S. Basu, A.K. Debnath, Power Plant Instrumentation and Control Handbook, Elsevier, November 2014. http://store.elsevier.com/Power-Plant-Instrumentation-and-Control-Handbook/Swapan-Basu/isbn-9780128011737/.*

comprising a suitable filter, di/dt arrestor, etc. An isolation transformer isolates the system from the input supply. It also helps in developing a multiphase rectifier circuit as shown in Fig. VIII/4.6.0-1A, which shows 12 diodes in a multiphase rectifier circuit to convert the AC supply (50/60 Hz) to a DC circuit. There is a filter to smooth out the DC voltage; the multiphase rectifier circuit is used to obtain better DC voltage. The smooth DC is fed to the inverter section. In the inverter the DC voltage is transformed into AC voltage (see a standard book on power electronics for inverter action), with the help of a silicon-controlled rectifier or an insulated gate bipolar transistor (IGBT), which is an advanced three-terminal power semiconductor switching device working on a minority carrier. IGBT has high-input impedance combined with the capability to handle high bipolar current. It combines the advantages of MOSFET and BJT and it is a voltage-controlled device. IGBT is used to turn the DC voltage on and off, and the DC voltage provides bipolar pulses of equal magnitude. In the control board the set point is compared, and it regulates turning on the waveform-positive half or waveform-negative half of the power device. The longer the device is on, the higher the output voltage and the higher the frequency and vice versa. The power device is turned ON/OFF by a carrier frequency, also known as a switching frequency. The higher the switching frequency, the higher will be the resolution of the pulse width modulation (PWM), so it is the smoother waveform of the AC signal. For further details Chapter VI of the author's book [17] may be referenced.

Prior to closing the discussions on the belt scale/belt weigher or weigh feeder we look into the details of various accessories, including the sway switch, zero speed switch, etc.

4.7.0 Conveyor Accessories: Safety Switches

For conveyor and human safety there are a few switches and accessories that are used for belt scale/belt weighers or weigh feeders. Local start/stop push-button stations and deinterlock switches are mounted near each piece of equipment for starting and stopping during test/maintenance of the system. A list of major items includes but is not limited to:

- Local start/stop;
- Pull chord switch;
- Belt sway switch;
- Speed switch (zero speed switch).

All these are used in the motor circuit of the conveyor as a safety interlock.

4.7.1 LOCAL START/STOP SWITCH

Normally, near the conveyors/Feeders there will be a box containing a local start and stop switch or push buttons near the conveyor. In some, along with the local start/stop push button, there are local indication running and stop lamps. For some countries, like India, these are mandatory as per electricity legislation. A local stop push button is used in the motor control circuit as a safety interlock in the sense that when this is operated the motor stops immediately. Local start push buttons may be used for local maintenance/testing/calibration.

4.7.2 PULL CHORD SWITCH

These are used to stop the conveyor in the case of an emergency. Rope-operated emergency switches can be mounted at equidistant places on either side along the conveyor. When pulled, the switch remains in a latched position unless it is manually reset, to avoid accidental restart. When the rope is pulled from any side, the switch is operated through lever. Normally, the lever is at 45 degrees on either side, so when pulled a snap action occurs so that the switch stays put and operates with moderate torque. These are available in an IP 55/65 enclosure (flameproof or commonly a suitable class II enclosure). A contact rating of 10/15 A at 500 V AC in changeover contact or 1 NO/1 NC is standard.

4.7.3 BELT SWAY SWITCH

To protect the conveyor from damage due to misalignment, these switches are used. The switches can be mounted at equidistant (normally 25 M) places on either side along the conveyor. In the case of excess sway, an edge push operating lever (45 degrees on either side when the angle changes to, e.g., 30 degrees) actuates the switch; these may be self-resettable. Normally, belt sway switches are available in IP 55/65 enclosure (flameproof or a commonly suitable class II enclosure). The contact rating is 10/15 A at 240 VAC.

4.7.4 SPEED SWITCH (ZERO SPEED)

Monitoring of speed is essential in an automation system. In speed control-modulating loops, a continuous monitoring speed is required, whereas a zero-speed switch is required for general conveyor operation. Also under-/overspeed switches can be used. Noncontact-type sensors are used for speed monitoring. These are mounted near the rotating device with a metallic flag. Thus, pulses are generated as the flag passes, and the same pulse is sent to a conditioning device. When the pulse count goes beyond a set point output, the relay operates to give contact. The speed settings, generally, are adjustable from 5 to 5000 RPM and may be self-resettable. Normally, they are available in IP 55/65 enclosure (flameproof or a commonly suitable class II enclosure). A contact rating of 10/15 A at 500 V AC in changeover contact or 1 NO/1 NC is standard.

The discussion on belt weighing systems comes to an end here and we now explore the possibility of solid flow measurement utilizing microwave signals.

5.0.0 NONCONTACT TYPE MICROWAVE SOLID FLOW METERS

Microwave technology has been applied for solid flow measurement. These noncontact, nonintrusive solid flow meters are mainly used for measurement of powder and solid materials, which are free-falling and/or pneumatically conveyed in a pipe. The basic idea behind this type of flow measurement has been discussed in Subsection 3.2.3.1 of Chapter I. Since these are mounted from the outside, they are easier to install. Also, maintenance requirements and costs are low. They can be used to measure powder and other solid materials with dimensions between ~0.001 μm to 20 mm in diameter.

5.1.0 Descriptive Details of Microwave Solid Flow Instruments

It measures moving particles only, so any deposits will not have an effect on the measurement. The discussion starts with the principles of operation. Also Section 7.0.0 of Chapter X may be referenced for further discussions on microwave solid flow monitors.

5.1.1 PRINCIPLES OF OPERATION

As stated in Subsection 3.2.3.1 of Chapter I, this instrument consists of one transreceiver which creates a low-energy microwave field in the pipe flow measuring region, as shown in Fig. I/3.2.3.1-1. On account of moving particles, a part of the microwave signal will be reflected back by the particles to the transreceiver. The intensity of the reflected Doppler-shifted energy is measured by the receiving sensor at the transreceiver. This small signal is sent to a converter which in turn converts a small signal into a suitable signal that it sends to the computing electronics, whereby a unique algorithm for the mass flow rate is computed and proportional 4–20 mADC is given as output. Since the meter measures the Doppler shift, it is applicable to moving particles only.

5.1.2 METER DESCRIPTION

The meter consists of components, such as a flow tube, a sensor as shown in Fig. VIII/5.1.0-1, a signal converter, and computing electronics. The meter gives proportional 4–20 mADC output along with alarm contacts. As stated earlier, there are two methods for solid flow measurement by a microwave flow meter. One is free falling and the other is pneumatic conveying. Therefore, the final

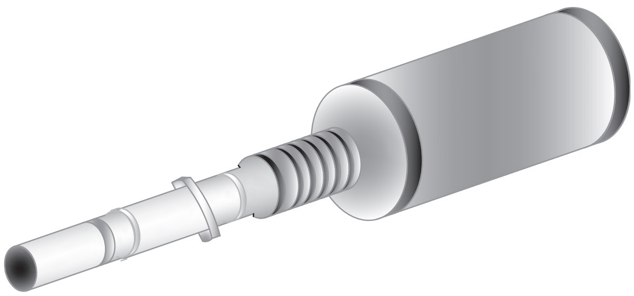


FIGURE VIII/5.1.0-1 Microwave solid flow meter.

accuracy of the meter depends on the material type, material conveying and installation. Compared to pneumatic flow applications, gravity flow applications are more reliable for mass flow reading compared to pneumatic flow applications, which have more variables, such as gas flow conditions and suspension of particulates in the conveying line.

To mount the equipment a hole for the mounting plug is first drilled into the conduit. The sensor is installed in line with the wall and therefore is wear-free. The meters are available for a wide range of pipe sizes, from 50 to 600 mm. These are available in various enclosure classes and associated computing units with a variety of display styles. The meters are installed in the pipe by different thread styles, such as M22 × 1.5 mm DIN/ISO 13 or G1 ½″ mostly through the use of welding branch (SS). Normally meters are provided with local displays of rate flow and totalized flow display in the computing electronics. The output from flow meter can be used for remote transmission also. We now explore the features and applications of this meter.

5.2.0 Features and Applications of Microwave Solid Flow Instruments

In this section the features and application details of microwave solid flow meters are outlined.

5.2.1 FEATURES OF MICROWAVE SOLID FLOW METERS

The following are important features of microwave solid flow meters:

1. Measurement of free-falling and pneumatic conveyed solids;
2. Sturdy nonintrusive sensor measurement flush with wall and noncontact easier installation. Also free from risk of radiation as in case of nucleonic instruments;
3. Suitable even for very low flow rates;
4. Measures and detects only “moving” particles, not deposits;
5. Faster measurement and quick sensitivity adjustment capability;
6. High operating safety;
7. Continuous in-line flow measurement for solids without a weighing scale;
8. Easy and simple installation in existing pipework;
9. Low maintenance requirement and cost.

5.2.2 APPLICATIONS OF MICROWAVE SOLID FLOW METERS

The following are the major application areas for the solid flow meter:

1. Capable of monitoring variable flow quantities due to disturbances in different densities;
2. For proper mixing of additives;
3. Capable of measuring all solids and many dusts within the sizes mentioned earlier, granular materials, powder/dust such as coal dust/saw dust, etc.;
4. **Major industrial applications include the following:**
   - Utility (power plant for pulverized coal);
   - Cement and mining beneficiation;
   - Chemical plants;
   - Plastic industries;
   - Petroleum;
   - Agriculture and food grains;
   - Building materials industry;
   - Recycling process industries;
   - Rubber and synthetic industries;
   - Wood dust;
   - Ceramics production;
   - Detergent industry;
   - Fertilizer industry;
   - Glass production.

5.3.0 Specification of Microwave Solid Flow Instrument

A brief specification of a microwave solid flow meter has been presented in Table VIII/5.3.0-1.

There are not many manufacturers of this flow meter. The data presented here are data from established manufacturers and as different data are available from various manufacturers, the best possible data have been selected, which may not match with any particular manufacturer. The reader is requested to use the data sheet as a base document and based on the intended application chose the most suitable meter in consultation with the manufacturer.

TABLE VIII/5.3.0-1 Specification for Noncontact Type Microwave Solid Flow Meter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Application	Flow of different kinds of solid and powder of different sizes both in free-falling conditions or pneumatic conveying		
2	Operating temperature	−20 to 90°C		
3	Ambient temperature	−10 to 60°C		
4	Operating pressure	Up to 60 bar		
5	Humidity	Product dependent		
6	Particle size	0.01 μm to 20 mm		
7	Pipe sizes	Up to 600 mm diameter		
8	Enclosure type	NEMA 4X IP66		
9	Material in touch with process	304S S (1.4307) or 316 SS (1.4571) and polyamide 6.6 welding branch AISI316Ti		
10	Measuring frequency	K band (24, 125 GHz)		
11	Sensor power	Through controller		
12	Power supply	115 VAC/24 V AC/DC or 230 VAC/24 VDC		
13	Transmitter	Mostly, Din Rail mounted		
14	Controller and remote unit	Remote mounted with display of suitable IP rating		
15	Controller enclosure	Desktop, 19″rack mounted or field enclosure		
16	Output	4–20 mADC, alarm contact, RS232/RS485 link for external interface, CAN network support		
17	Display	Backlit LCD, LED with necessary dedicated keys, and/or TFT/LED monitor SVGA display with keyboard		
18	Software	To support flow computation and programming		
19	Accuracy	0.5%–2.5%		
20	Response time	1 s		
21	Hazardous application	Yes, ATEX certification possible		
22	Accessories	Welding branch as required		
23	Special feature	Special cable for interconnection and others to specify		

Like with the microwave flow meter, there is another noncontact type solid flow-sensing instrument that uses nuclear technology, which is explored in the next section.

6.0.0 NONCONTACT TYPE NUCLEONIC SOLID FLOW METERS

This is another example of a noncontact type solid flow measurement system universally used in many plants for its versatility. One thing to be remembered is that it measures the density of material or weight of material in a unit area as indicated in Subsection 3.2.3.2 of Chapter I. Since nucleonic instruments are subject to human hazards it is an absolute necessity that these are handled only by licensed personnel with sufficient experience and training and the manufacturer's instructions should be followed. Normally the symbol that is shown in Fig. VIII/6.0.0-1 is marked on nucleonic instruments. For other similar symbols and symbols for ex-proof IS instruments, the author's book [2] may be referenced.

FIGURE VIII/6.0.0-1 Caution symbol. *For other symbols see the author's book S. Basu, Plant Hazard Analysis and Safety Instrumentation Systems, Elsevier; IChemE, 2016, http://store.elsevier.com/Plant-Hazard-Analysis-and-Safety-Instrumentation-Systems/Swapan-Basu/isbn-9780128037638/ may be referenced.*

Normally all these instruments bear a caution note, with the following being typical:

> *All Nucleonic/Radiometric/Gamma measuring systems utilize* **radioactive substances** *which are manufactured in compliance with official regulations and are protected by suitable shields.* **Any hazards to personnel due to built-in radioactive substances can be ruled out, provided they are handled properly, as prescribed by laws and regulations. These instruments/measuring facilities may be operated only by specifically licensed persons with sufficient expertise and training**.

Therefore, suitable necessary precautions should be followed.

Nucleonic or radiometric solid flow meters can be used to determine the load/solid flow in the following:

- On conveyor belts;
- On screw/chain/apron conveyors;
- For free-falling materials (nonbinding materials);
- For materials in pneumatic conveying.

  In the case of free-fall measurement, the measurements should be carried out at a place very close to the discharge station. In that case, it would reduce the theoretical rate of fall at the measuring point, otherwise as per the law of gravity the rate of fall would rise with increasing distance. So, with a rising rate of fall the weight per area, and hence the accuracy of the measurement, would decrease. There are two kinds of each of source and detector:

- *Source: Point source* or *rod source*;
- *Detector: Point detection* or *rod type detector*.

  Rod type sources are used in the case of free-falling material solid flow measurements.

  On many solid conveying systems, a nucleonic/radiometric weighing system is the only suitable method for determining mass flow. This type of measurement is very suitable for hot clinker conveying in a chain/apron conveyor. During the discussions in Subsection

3.2.3.2 of Chapter I, illustrations such as in Fig. I/3.2.3.2-1 have been shown with rod sources, whereas here both types are illustrated. The basic theory of measurement has already been discussed in Subsection 3.2.3.2 of Chapter I, and so further discussions give functional details of nucleonic/radiometric instruments for solid flow measurement.

6.1.0 Principles of Operation for Nucleonic Mass Solid Flow Meters

From the discussions in Chapter I it is clear that for nucleonic/radiometric solid flow measurement, a radiation source and a detection unit are necessary. The energy absorption of radioactive material is dependent on the load on the conveyor. Any material between the source and detector reduces the intensity of radiation to be measured at the detector. The radiation is absorbed by the product on the belt and the attenuated radiation is picked up by a detector. The output of the detector is evaluated by intelligent microcontrollers/embedded systems. Therefore, nucleonic/radiometric instruments illustrate the physical law of attenuation of radiation as explained in Subsection 3.2.3.2 of Chapter I from where we get that the attenuation of the radiation is dependent upon the height and bulk density of the material. The product of height and bulk density is the weight per area! When the mass per unit of area is multiplied by the material width, the result is the mass over unit length of the conveyor. When this product is again multiplied by the speed, this results in the desired mass per time unit. At this point it is worth noting that the contamination of the product being measured or the pipeline wall by gamma radiation is not possible. In radiation type solid flow meters, Caesium-137 or Cobalt-60 isotopes are normally used as radiation sources. The radiation source emits focused gamma rays, which are attenuated when penetrating the bulk material and the conveyor belt/pipe. The detector on the other side of the conveyor belt/pipe receives the radiation, the strength of which is proportional to the bulk density of the material. As stated earlier, this type of measurement can be utilized for conveyors and in pipelines.

1. **Solid flow in a conveyor:** In the case of conveyor it is necessary to measure the speed of the conveyor. Conveyor speed can be inputted as a constant value manual input. Alternatively, it can be used with a constant speed conveyor giving constant speed input. In most cases these are used in conjunction with a tachometer to measure the speed of the conveyor. Therefore, for a conveyor, the following measurements are carried out:
   - Measurement at constant belt speed;
   - Measurement with a tachometer;
   - Measurement with moisture compensation.

   The attenuation occurring during maximum conveyor throughput determines the choice of source [34]. It is worth noting that radiation type solid flow measurement in a conveyor is not suitable if the conveyor loading is low, i.e., below 10% of full scale, and if the conveyors run for a short period of time, e.g., <10 min [4].
2. **Free-falling/pneumatically conveyed materials:** In the case of free-falling or pneumatically conveyed material the measurement is made very close to the discharge point. The radiation source and detectors are placed at the opposite sides of the pipe/chute. As the measuring geometry is constant, the resulting attenuation is directly proportional to the solids concentration. Hence, with know discharge area n=mass per unit area is known. Therefore in combination with the material velocity, the required mass flow can be accurately determined. There are a few configurations and frameworks for nucleonic/radiometric measurement of solid flow measurements. We first explore such possibilities.

6.2.0 Configurations for Nucleonic Mass Solid Flow Meters

As stated earlier, there are two types each of radiation source and detector, so for effective measurement it is essential that proper measurement configurations should be implemented, such that it covers the given measuring range continuously. The measuring configuration shall be such that the source and detector form an optimum geometry, covering a measuring field of equal size [34]. The different such configurations depend on: the conveyor facility available at the plant, plant-specific installation, and operational constraints, etc. These are the major issue normally considered during the planning stage.

Nucleonic/radiometric measuring systems consists of the following:

1. Radioactive source inside a shielding container;
2. Holding device for a detector;
3. Measuring frame with a shielding container or a holding device with shielding for free-fall measurement;
4. Detector with a necessary cooling system;
5. Intelligent computational or evaluation unit;
6. Speed-measuring device such as a tachometer with encoder (where applicable);
7. The power supply system;
8. Other accessories, such as cable and wiring system.

As per the measuring principles, the amount of radiation attenuation is detected by a detector. The output of the detector is connected to an intelligent computing/evaluation unit. For measurements in conveyors, depending on the applicability, a tachometer with encoders mounted on conveyors could be connected to the intelligent electronics referred to above. For speed measurements on a *conveyor belt*, the tachometer should be attached to the *tail* pulley. For speed measurements on *chain/apron and screw conveyors*, the tachometer is attached to a rotating axle with the help of a suitable flexible coupling.

There are two types of radiation source, rod type and point source type, both of which put inside the shield. Similarly, there two types of detectors, rod type and point type. There are different solid flow measurement configurations (both for solids in conveyor/free-flowing solids in pipe/chute) due to variations in source and detector unit types. Based on the measurement tasks, plant-specific issues, such as measurement and conveyor facility available at the plant location, a suitable configuration should be chosen for the specific application. The chosen measuring configuration should be such that the source and detector form an optimum geometry covering a measuring field of equal size [34]. Various configuration issues are discussed in the following subsections to give further details.

6.2.1 CONFIGURATIONS FOR SOLID FLOW MEASUREMENT IN PIPES

For free-falling solid flow measurement, the measuring point should be close to various discharge stations. These can be mounted on a pipe, chute, or even free-fall as discharge of vibrator trays, transfer chutes, screw conveyors, etc. Typical such arrangements have been depicted in Fig. VIII/6.2.0-1. In this connection Fig I/ 3.2.3.2-1 (RHS) may be referenced also Rod type sources are used for free-falling and pneumatically conveyed solid materials. The measuring device can simply be mounted on to existing fall-pipes. It consists of a shielding with a rod source and a variably adjustable holding plate for the detector [34]. As stated in section 6.1.0.2 in these cases material velocity for free falling material needs to be known for solid flow computation.

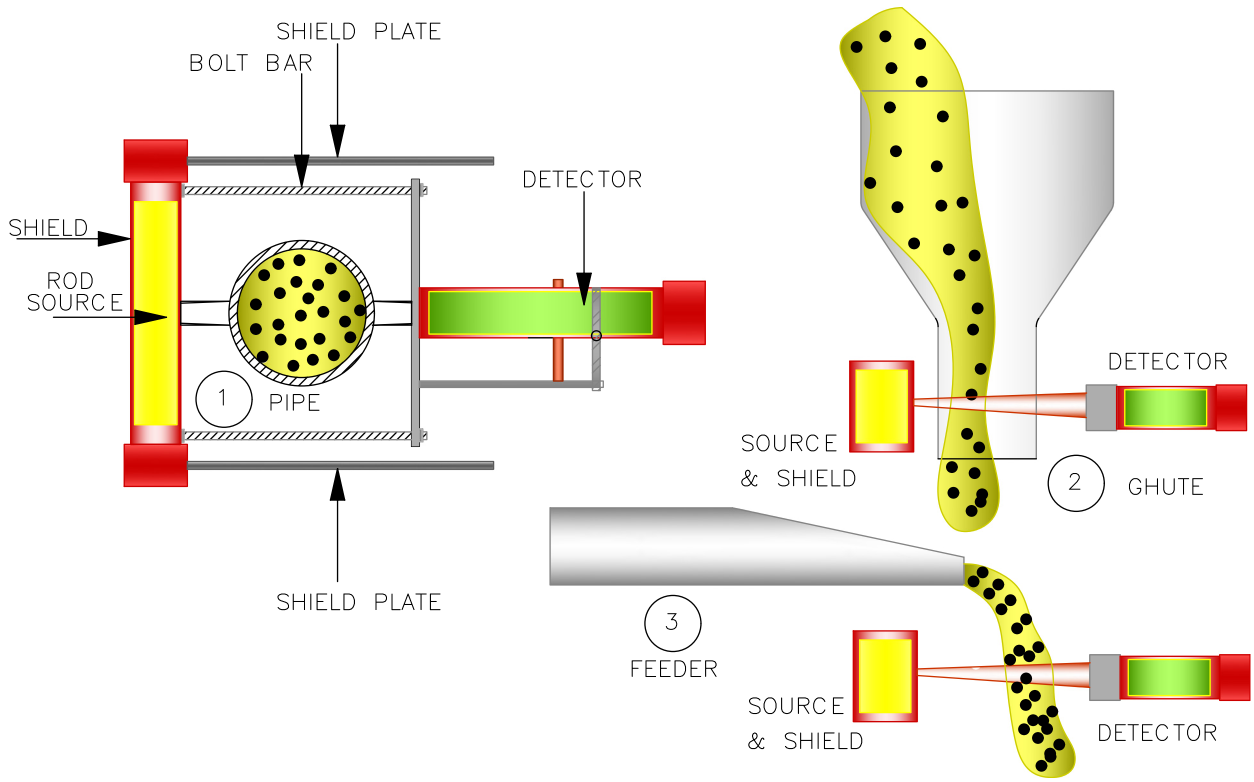


FIGURE VIII/6.2.0-1 Free-falling material flow measurement.

6.2.2 CONFIGURATIONS FOR MEASUREMENT IN CONVEYOR SYSTEMS

There are two major configurations for solid flow measurement with conveyors. These are listed below. There can be other configurations, such as two-point sources also.

1. **Rod type source:** Normally for measurement, the foot of the measuring frame is utilized for mounting the radiation source complete with the shielded container with the rod source inside with the exit channel pointing towards the detector above. The radiation source is installed below the conveyor as shown in Fig. I/3.2.3.2-1. The detector is mounted directly above and the line of view of the radiation exit channel of the shielded container for radiation source. This is applicable for conveyor belts, screw conveyors, and chain conveyors.
2. **Rod detector:** For a rod detector configuration as shown in Fig. VIII/6.2.0-2, there will be one point source mounted directly above the conveyor in a beam of the measuring frame. The rod detector is mounted at the foot of the frame. The measuring frame is fixed to a sturdy base. It is worth noting that the rod detector can also work with a rod source.

Having discussed the various possible configurations with different radiation sources and detection types, it is time to look into the details of various units in nucleonic instruments.

6.3.0 Descriptive Details of Nucleonic Solid Flow Measuring Systems

In this section, the essential parts of nucleonic instruments deployed for solid flow measurement shall be discussed. The discussions start with the radiation source (Fig. VIII/6.3.0-1).

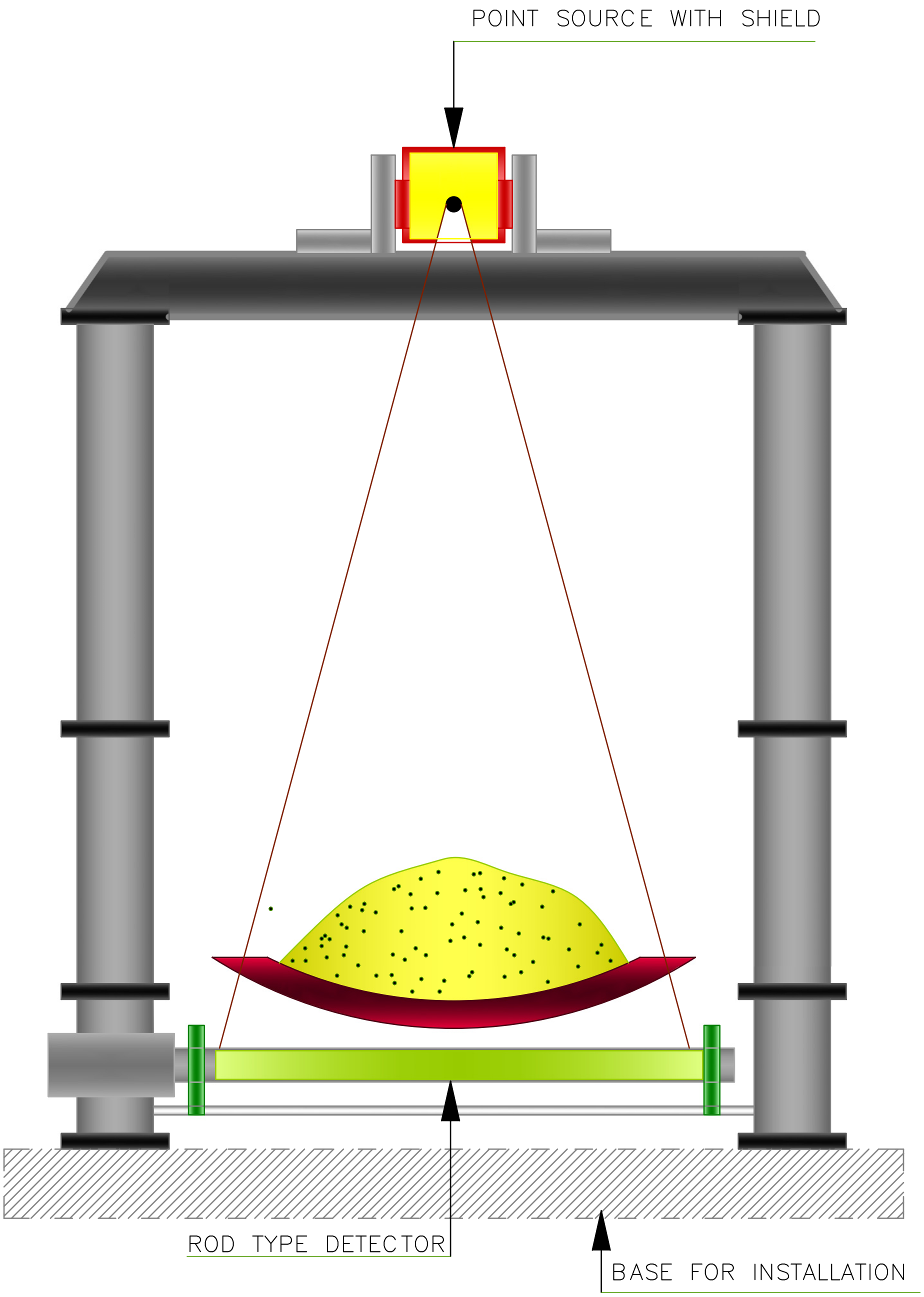


FIGURE VIII/6.2.0-2 Point source rod detector.

6.3.1 RADIATION SOURCE

Co60 and Cs137 are commonly used as the radiation source, but other substances, such as Am241 and Kr85, are also used. A comparative chart for both has been presented in Table VIII/6.3.1-1.

Radiation sources (such as Co60 and Cs137) are equipped with a lead-filled steel pipe as shielding (lockable), with a radiation exit channel. When the exit channel is closed, the radiation hits the steel shielding. In an installed condition, when the radiation exit channel is opened, it should be exactly aligned with the scintillation counter that is installed on the opposite side. There can be different radiation exit angles, especially for the point source. Normally, the exit angle is determined based on the geometry of measurement. As a precautionary measure; *"Radioactive sources for*

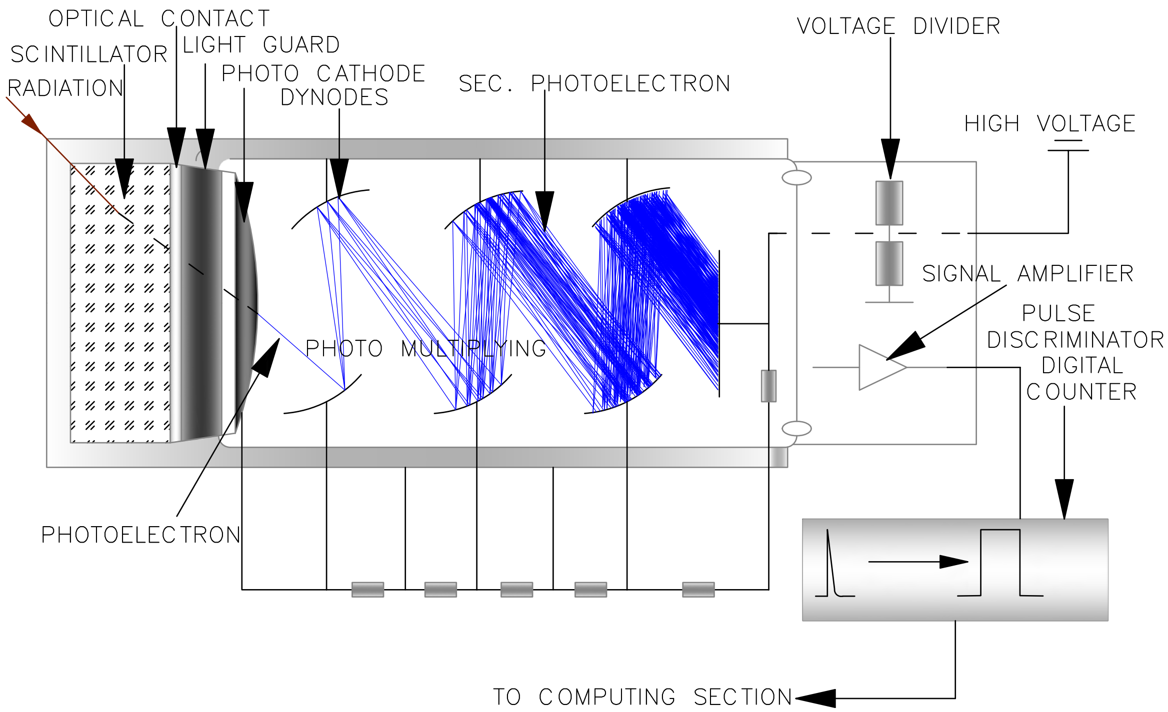


FIGURE VIII/6.3.0-1 Detector for nucleonic solid FM.

TABLE VIII/6.3.1-1 Comparison of Commonly Used Radiation Sources

Characteristics	Co60	Cs137
Energy level	1.17−1.33 MeV	0.66 MeV
Half life	5.27	30 years
Flow use	High load	Normal belt load
Decay to	Ni60	Barium 137

industrial applications are always 'encapsulated radioactive substances' which are tightly welded into a sturdy stainless steel capsule" [34], so that the radioactive substance cannot leak out.

6.3.2 RADIATION DETECTION

In this type of nucleonic/radiometric measurement, scintillation counters as indicated in Fig VIII/6.3.2-1, are used as detectors as they are highly sensitive to gamma radiation. A typical scintillating counter has been depicted in Fig VIII/6.3.0-1. The detector comprises the following parts:

1. Scintillating medium;
2. Photomultiplier;
3. Electronic processing unit.

There are two types of scintillating medium: sodium iodide crystal doped with thallium (TI) and an organic (plastic) scintillating medium such as polyvinyltoluene (PVT). The former produces more photons per MeV, and is comparatively more expensive than the latter.

An electronic processing unit with embedded electronics is the heart of the system and carries out the following functions so that the system can work properly:

- Maintenance of the system configuration;
- Counting of pulse rates;
- Regulation of high voltage for scintillator operation;
- Monitoring of probe health, including temperature condition;
- Control of the cooling system;
- Other system controls;

Scintillating counter: It is a device used to detect and measure ionizing radiation utilizing the excitation effect of incident radiation on scintillating medium which can be inorganic type such as NaI containing small amount of thallium or organic type (including liquid) such as polyvinyltoluene (PVT). In scintillator energy from electron-hole pair can be liberated as light. When the excited ion goes to its ground state a bluish light is seen so in NaI(TI) scintillator a blue light can be observed.

FIGURE VIII/6.3.2-1 Scintillating counter.

- Data exchanges;
- Supply and communication with the intelligent electronic evaluation unit.

On absorption of radiation, scintillating material generates a light signal, i.e., the *scintillator* (scintillating medium) converts the energy from the incident gamma radiation into light in the visible spectrum. The number of visible light flashes per unit of time is a measure of the intensity of the incident radiation. With very short light flashes a high resolution is achievable. These light flashes are detected by a photodetector photomultiplier to amplify the signal. Electrons released from this photomultiplier are then moved to several dynodes (intermediate electrodes in a photomultiplier to generate additional electrons). These dynodes are in cascade connection mode so that electrons are accelerated by high voltage to release further electrons and in this process effectively every electron triggers an electron avalanche. The electronic processing unit of the detector counts these pulses and transmits the same to the intelligent computing/evaluation unit of the measuring system. For high accuracy and long-term stability, the integrated processor automatically adjusts the optimum operation point of the photomultiplier, monitors the limit values, and stores all detector-specific data [34]. The detector assembly is housed in an SS enclosure of suitable IP rating.

6.3.3 INTELLIGENT COMPUTING AND EVALUATION UNIT FOR NUCLEONIC FLOW METERS

An intelligent computing and evaluation unit is not only a simple signal processing unit to produce an output but should be considered as an intelligent device with its own intelligence for interfacing with the instrument as well as the operator interface. The high computing speed and digital signal processing capability of modern computing and evaluation units comes from the state-of-the-art technology incorporating a 32-bit microcontroller/embedded programmable processing unit. As a result, high precision is also expected from the device. With high packaging techniques it is possible to accommodate a number of units in a typical 19″rack. However, there can be a number of other versions available for wall/panel mounting. Functionally it should be able to support continuous/discontinuous measurement and batch operation. It consists of the following parts.

1. **Unit interface details:** The operator interface comprises of:
    - *Display:* High-quality displays with backlit LCD/LED or LED screen;
    - *Dedicated keys:* Dedicated keys for carrying normal operation, calibration, and setting up of the instruments;
    - *Storage:* Data storage unit flash/other memory devices with battery back up;

- *Software support:* Necessary software helps to carry out menu-driven operation and programming. Software also supports diagnostic programs to maintain the integrity and proper operation of the measuring system;
- *Interfaces:* Various interfaces, such as RS 232/485 links, serial interface for printer;
- *Communication and network:* Most modern units support fieldbus communications, which include but are not limited to Foundation fieldbus, Porfibus, and various networks like Ethernet and CAN. Some versions are available which also support the HART protocol.

2. **I/O units:** Modern intelligent computing and evaluation units also provide the following:
   - *Analog input:* 4–20 mADC (e.g., moisture correction);
   - *Analog and pulse output:* 4–20 mADC or pulse output;
   - *Tachometer input:* 4–20 mADC or encoded signal;
   - *Digital I/Os:* There are a number of DI/O for supporting associated interlock (i.e., conveyor stop/batch operation) or output for alarm functions, etc. Digital outputs can be potential free contacts of relays or open collector outputs.

   It is now possible to recognize the various features and applications of the system.

6.4.0 Features and Applications

In this section some features and application areas of nucleonic instruments for solid flow measurements are discussed.

6.4.1 FEATURES OF NUCLEONIC SOLID FLOW METERS

The following are major features associated with nucleonic solid flow meters:

1. Contactless measurement;
2. Safe operation;
3. High level of repeatability;
4. Precise accuracy;
5. High sensitivity;
6. Long-term stability;
7. Independent of process conditions (temperature/pressure);
8. Moisture correction possible;
9. No recalibration necessary;
10. Immunity to interface;
11. Moderately expensive.

6.4.2 APPLICATIONS OF NUCLEONIC SOLID FLOW METERS

It is possible to easily mount externally on existing pipelines, chutes, or on the discharge of vibrator trays, transfer chutes, etc., as shown in Fig. VIII/6.2.0-1. Solid flow measurement in conveyors as shown in Fig VIII/6.2.0-2, can also be easily measured and one of its major advantages is that it is independent of process conditions. Hot clinker measurement in a chain/apron conveyor is a classical example of the application of a nucleonic solid flow meter. It is often used for solid flow of the following:

- Calcium carbonate;
- Calcium chloride;
- Coal dust;
- Ash;
- Hot clinker.

6.5.0 Specification of Noncontact Type Nucleonic Solid Flow Measuring Systems

A brief specification of nucleonic solid flow meters has been presented in Table VIII/6.5.0-1. There are not too manufacturers of this type of flow meter. The data presented here are data from established manufacturers and as different data are available from various manufacturers, the best possible data have been selected, which may not match with any particular manufacturer. The reader is requested to use the data sheet as a base document and based on the intended application, the most suitable one chosen in consultation with the manufacturer.

Intelligent computation and evaluation unit specification should be read in conjunction with Section 6.3.3.

TABLE VIII/6.5.0-1 Specification for Noncontact Type Nucleonic Solid Flow Meter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Application	Dust granular solid materials. Nonbinding materials for pipe flow. Measures flow in conveyor, free-flowing material, and pneumatically conveyed material		
2	Measuring range	0.5–1.8 m		
3	Flow range	Selectable from 0 to 200 kg/h to 10000 t/h		
4	Temperature	Operating: −40 to 60°C Storage/ambient: −40 to 70°C Stability: 0.5% FSD		
5	Cooling water	Possible for detection cooling		
6	Source/detector style	Both point and rod		
7	Detector types	Inorganic: NaI (TI) crystal; organic: plastic scintillator		Length for rod detector as per manufacturer
8	Measuring frame	As per manufacturer		
9	Hazardous application	Yes, exproof ATEX rating possible, also IC connection		IC = intrinsic safety
Intelligent Computing and Evaluation Unit (See section 6.3.3 also)				
10	Display	High-quality displays with backlit LCD/LED or LED screen		
11	Power supply	110/240 VAC 50/60 Hz; 18–32 VDC (24 VDC)		
12	I/O types and other details of intelligent unit	Refer to Section 6.3.3		
13	Contact ratings for digital O/P contacts	AC: 250 V, 1 A, 230 VA or DC: 220 V, 1 A, 60 W		
14	Accessories	Cables of required rating, tachometer with encoder, mounting frame		
15	Special feature	To specify – if any		

Simple calibration can be performed by using theoretical coefficients. Maximum precision is achieved by means of comparative weighing with, e.g., a weighbridge.

With this the discussions on nucleonic solid flow meters have come to an end and we now discuss other miscellaneous solid flow metering systems which are used in industries for certain specific applications, such as screw and apron weigh feeding, capacitance type solid flow metering, etc.

7.0.0 MISCELLANEOUS SOLID FLOW METERING SYSTEMS

Instrumentation items discussed so far are quite popular in their usages and standard items. There are a few measuring systems that exist in industries which are also standard items but find their application mainly for specific usages in these industries. In this section brief discussions on these will be presented, enabling the reader to become well acquainted with these devices.

7.1.0 Screw Weigh Feeder

Screw weigh feeders are also used for metering different bulk solids like weigh feeders. These are available and used for different feed rates, bulk solids characteristics, and application-specific ancillary conditions as specifically as possible. Screw weigh feeders can be designed as speed-controlled screw weigh feeders for continuous feeding of bulk solids. Material is extracted directly from the weigh bin by screws. The activator in the bin ensures the even emptying and distribution of material to the two feeding screws.

7.1.1 OPERATIONAL DETAILS OF SCREW WEIGH FEEDERS

The principle of operation of a screw weigh feeder is similar to that for a belt weigh feeder. In the in-feed area, the screw is pivoted horizontally to transverse to the conveying direction. A force-measuring device, in the form of a set of load cells for weight measurement, is installed. The number of load cells depends on the screw feeder configuration and type. The measurement of weight can be carried out by placing the load cells at the support points for the screw conveyor at all four corners with the load distributed evenly. In case the material from the inlet falls/drops over the load cells, ideally a pivot point should be used as shown in Fig. VIII/7.1.0-1.

This is to reduce the impact of falling material on accuracy, and it this will reduce the dead load of the screw conveyor as the gear motor counterbalances from the pivot. The speed sensor should be mounted to the driving end and may be directly coupled with the drive as shown in Fig. VIII/7.1.0-1 or can be mounted on the screw shaft concentric with the center and a set screw applied to ensure consistent rotation with the screw conveyor. As the accuracy of the screw weigh feeder depends on the filling level of the screw, it is preferable that there is an upstream dosing device (e.g., rotary feeder, vibrating trough). Flexible couplings should be used at the inlet and discharge of the screw conveyor to avoid weighing accuracy due to loading and expansion of piping and ducts. The signals from a load cell and speed senor should

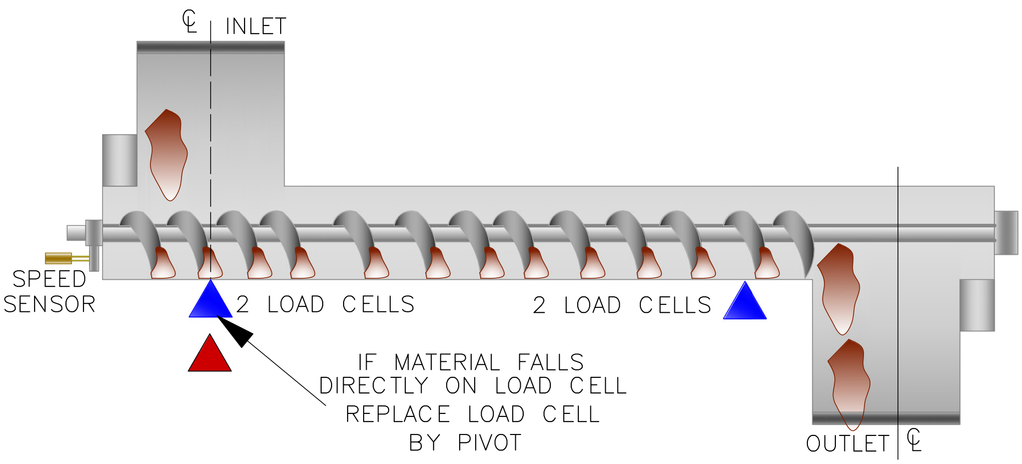


FIGURE VIII/7.1.0-1 Screw feeder with sensors.

be connected to a computing unit for calculation of flow rate in terms of T/h. Such a computing unit or weight controller can be used for the generation of a measurement error alarm, etc., already discussed. Screw weigh feeders can be open or enclosed types. The latter can be used for metering and weighing dusty, aggressive, or toxic powders with a capacity of around 60 T/h available on the market. For the open type the feeding capacity will be greater, as available on the market. Screw weigh feeders can offer an accuracy up to between 0.1% AR and 1.0% AR.

A general description of screw feeders/conveyors has been given in Section 1.1.4 in this chapter and hence is not repeated again. We now look into the selection of the screw feeder.

7.1.2 SIZING AND SELECTION OF SCREW WEIGH FEEDERS

It is possible to convert any screw conveyor into a screw weigh feeder provided the required details are made available. In the following such a conversion process is discussed.

1. **Screw capacity estimation:** The following information would be necessary for applying the components for a screw conveyor to be a screw weigh feeder.
   - *Screw feeder weight:* Weight of the screw conveyor when empty (tare weight);
   - *Length:* Length/distance between the centerline of the inlet to the centerline of the outlet;
   - *Diameter:* Diameter of the screw conveyor;
   - *Pitch:* Pitch of the flights of the screw conveyor;
   - *Normal Speed:* Revolutions per minute that the screw is rotating;
   - *Capacity estimation:* Weight of the material in the screw conveyor during normal operation;
   - *Bulk density:* Approximate idea about the bulk density of the material;
   - *Volume flow:* Volumetric flow per revolution;
   - After getting an idea of the mechanical details and flow parameter estimate it is time to calculate the sizing of the load cell.
2. **Load cell sizing:** The load cell capacity should be calculated as follows

   (guidelines given below are from [35], courtesy: Siemens):

   Required total weight = Weight of the screw conveyor + Weight of the material in the conveyor; Capacity necessary = Required total weight × 1.25% (safety factor). Nominal load cell capacity = Total weight/4 (when four load cells are used). Select the next highest load cell capacity available, unless it is more than 10% oversize.

   The live load (material) should be at least 10% of the load cell capacity:

   Weight of the material in the conveyor/load cell capacity × 100 = >10%, the load cell capacity is suitable; <10% the application may not be suitable for gravimetric weighing OR investigate an alternative load cell range.

7.1.3 TYPICAL FEATURES OF SCREW WEIGH FEEDERS

The following are general features of screw weigh feeders:

- All well-flowing materials such as cement, rock powder, quartz sand, cereals, granulates;
- Enclosed system, environmentally friendly, fire-resistant, when flammable mixture is fed into furnace, prevents its further propagation;
- Suitable for feeding into the rotary feeder of pneumatic transport, flange to placing of a filter or pressure compensation;
- Universal application, can be retrofitted into existing systems;

- Maintenance-friendly design;
- Screw weigh feeders in mounting frame are available for easy installation.

7.1.4 MAJOR APPLICATION AREAS OF SCREW WEIGH FEEDERS

The following are some of the application areas of screw weigh feeders:

- Measurement of continuous mass flow;
- Weight-controlled filling of tanks, containers, etc.;
- Weighing product.

We now look at apron weigh feeders in the following section. General description and mechanical details of an apron feeder have been discussed in Subsection 1.1.5.2 in this chapter.

7.2.0 Apron Weigh Feeders

There are a number of materials such as clay, marl, tuff, and silt which are not easy to handle, for feeding, etc. Therefore, on account of their dampness, stickiness, and instability, a standard weigh feeder cannot be used for weigh feeding. In such cases, apron weigh feeders are suitable. Apron weigh feeders feature an integrated weighing rail combined with the electronics treating the measured data and ensuring gravimetric proportioning with the desired precision. Speed measurement of an apron feeder is similar to that in a screw conveyor. Apron feeders have flexible type pan conveyors to adapt to any kind of bulk materials, the weigh feeder is suitable for a large variety of applications requiring proportional feeding. So, for reliable feeding of sticky materials, such as sludge, with a high degree of accuracy apron feeders are used. Operation of apron feeders is similar to that discussed in connection with screw weigh feeders. Apron feeders find their applications in conveying the following:

- Clinker;
- Granulated blast furnace;
- Petroleum coke;
- Clay;
- Clay and raw mix;
- Marl;
- Prozzolana;
- Gypsum.

7.3.0 Capacitance Type Solid Flow Meters

It is possible to measure solid material flow in free-falling mode and dense-phase, pneumatically conveyed bulk solids with the help of capacitance type flow measurement. In this method solid flow is measured in a correlation method. This is a nonintrusive type flow measurement method which utilizes a correlator and integrator and utilizes advanced software to get the rate flow and cumulative flow. This correlator and integrator can also be used to monitor and control the flow in pipes or the flow distribution through pipe networks.

7.3.1 CAPACITANCE TYPE SOLID FLOW MEASUREMENT

In this method of measurement there are two independent sensors and a correlator/integrator. These two independent sensors are the velocity sensor and capacitance-based concentration sensor. Both sensors are mounted directly on a pipe network as shown in Fig. VIII/7.3.0-1. The capacitance of the empty pipe and the pipe filled with material will be different. Therefore, with the changes in capacitance the concentration level of the material, i.e., the density of the material, is assessed. So, for a known pipe geometry, mass flow can be inferred when the velocity is measured and the two signals are correlated to compute the solid rate flow. In cross-correlation the time it takes for the material to travel between the points is measured. Signals from both sensors are sent as output to the intelligent correlator/integrator, to calculate the mass flow rate and cumulative flow. Plastic pellets and pneumatic conveyed coal for a blast furnace are classical examples of capacitance solid flow meters.

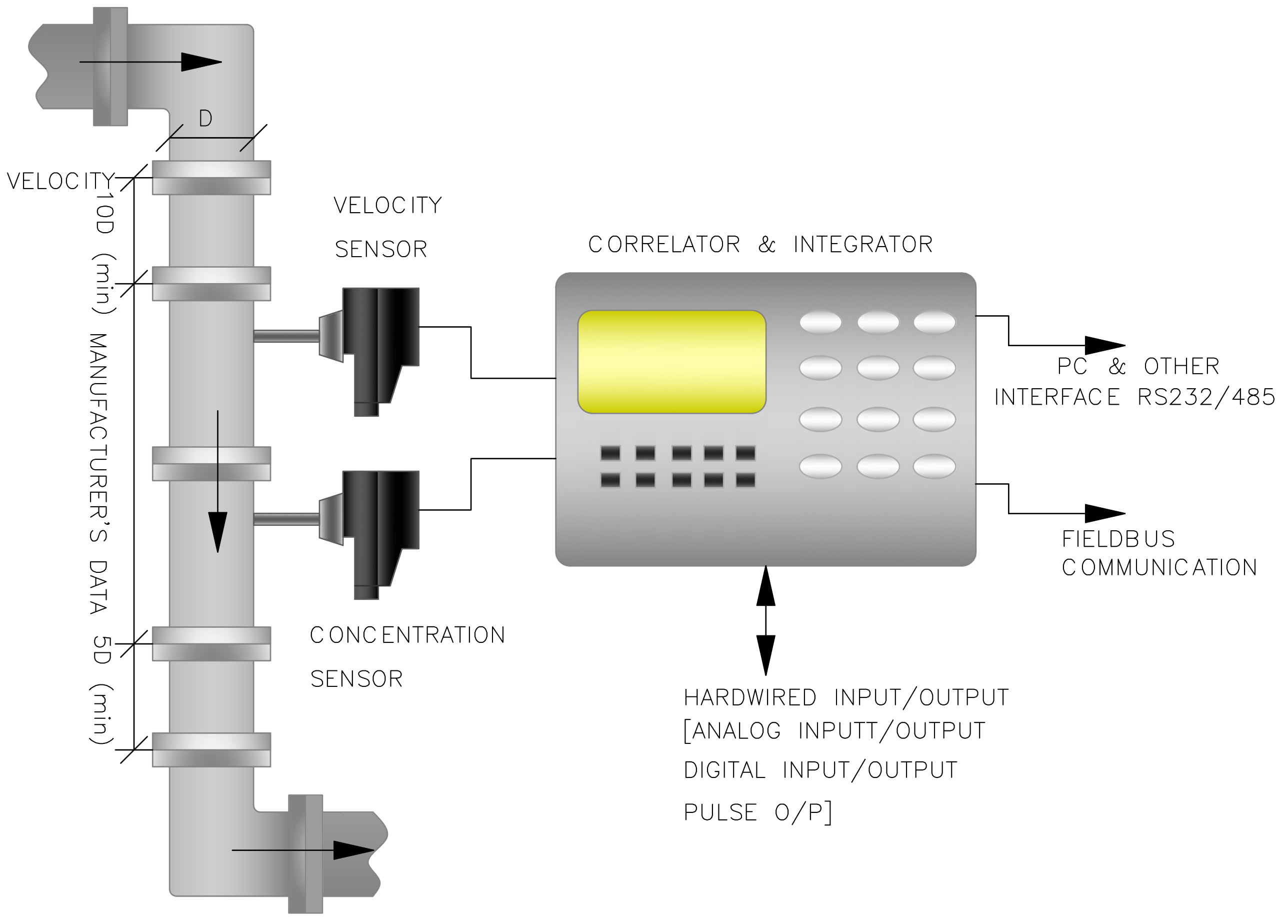


FIGURE VIII/7.3.0-1 Capacitance type solid flow meter. *Developed based on an idea from Thermo Scientific; Ramsey Granucor; Solid Flow Measurement System; Product Specification: thermoscientific.com/bulkweighing. Courtesy: Thermo Scientific.*

7.3.2 FEATURES OF CAPACITANCE TYPE SOLID FLOW MEASUREMENT

1. Nonintrusive flow measurement;
2. No moving parts, hence less maintenance prone;
3. Independent of pressure and temperature;
4. Easy installation into new or existing processes;
5. Sensors are available in different pipe sizes—from 15 to 200 mm; DN10 to DN200 (0.5−8.0 inch) pipe size [36];
6. Intelligent correlator provides advanced operator interface with self-diagnostics.

7.4.0 Force Flow Type Solid Weigh Meters

Force flow type measurements are deployed mainly for primary resin compounding. This type of weigh meter, in combination with a rotary valve, offers an alternative to belt weighing, which may not be suitable for base resin (fluff) feed, especially during the proportioning of additives prior to pelletization. The main concern here is the extraction of material from the storage unit and ensuring the rotary valve is full. Also, the speed of the rotary valve is important. Therefore, if necessary a rotary delumper can be used to reduce particle size. The overall footprint

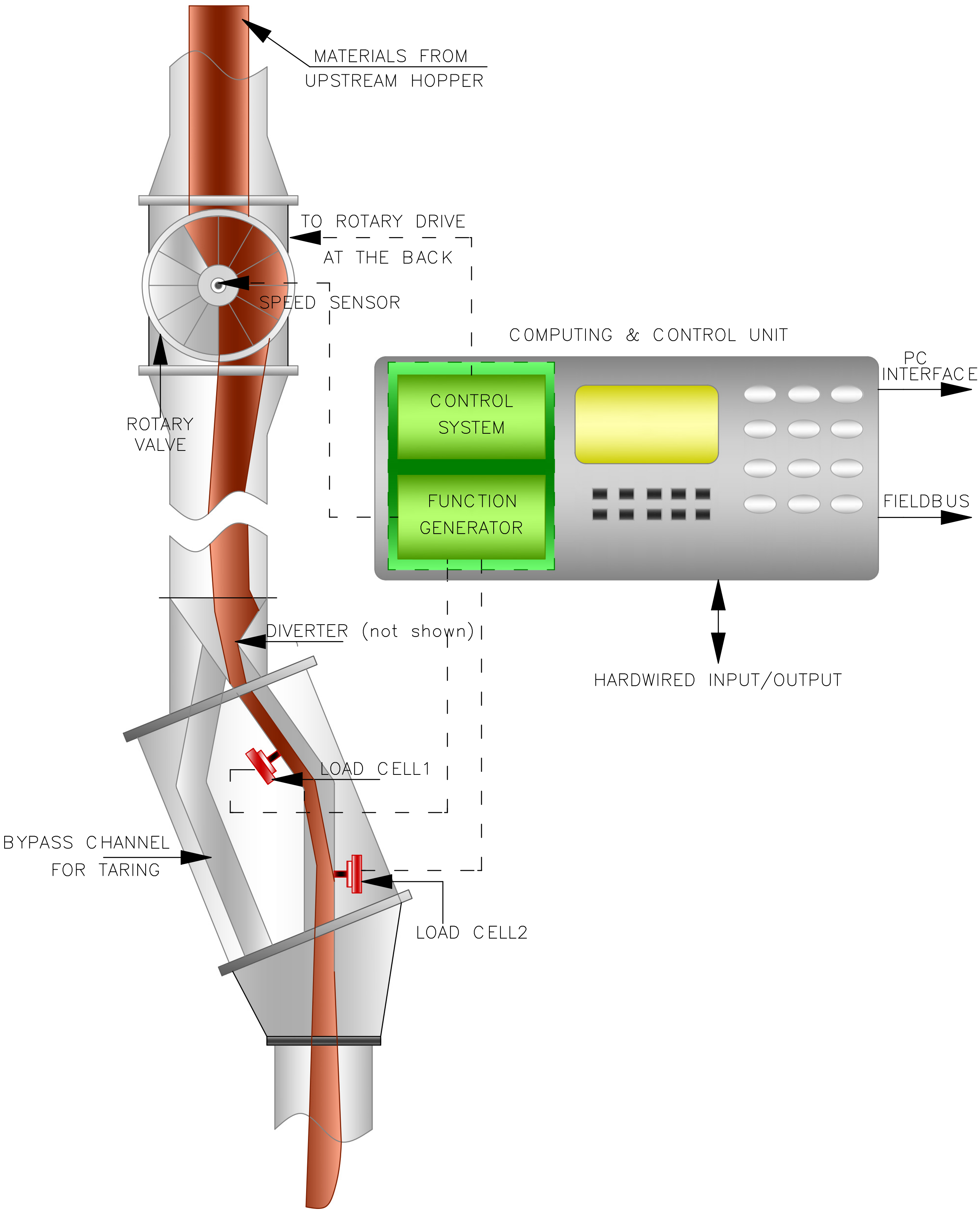


FIGURE VIII/7.4.0-1 Force flow weigh meter.

of the meter is much less than that of a weigh feeder, but the height is greater.

7.4.1 PRINCIPLE OF OPERATION OF SOLID WEIGH METERS

During operation, the rotary valve withdraws the material from the upstream hopper and discharges it to the flow meter. At the point of entry of the weigh meter at an upper measurement channel, it slides across an inclined surface as shown in Figs. VIII/7.4.0-1 to stabilize the vertical velocity component. Falling within the meter, the material is first deflected by an inclined channel and is then again redirected by a second, vertical channel. Each of these channels is provided with load cells 1 and 2, respectively, as shown in Fig. VIII/7.4.0-1. The load cell types normally are a vibrating wire type described in Fig VIII/7.4.0-2.

The forces experienced by these two channel sections are separately measured and combined to produce the gravimetric flow rate measurement. Based on this, the rotary valve speed is adjusted to produce the desired feed rate. Assuming constant speed of the rotary valve (manual value included in K), one gets,

$$q_m = K \cdot \frac{\sqrt{F_1 \cdot F_2}}{g \cdot l \cdot \cos \alpha} \qquad \text{(VIII/7.4.1-1)}$$

where F_1 and F_2 are the forces sensed by load cells 1 and 2, respectively. The length of the inclined part of the meter is represented by l and α is the angle of inclination with respect to a vertical line. In the case that there is variation in speed then the speed signal must be multiplied (K value will be readjusted). In Fig. VIII/7.4.0-1 such possibilities are shown. In any case, based on the measured value, speed adjustments may be necessary. As shown in Fig. VIII/7.4.0-1, there will be one bypass channel within the meter, which enables taring without process interruption.

7.4.2 PROS AND CONS FOR SOLID WEIGH METERS

As stated earlier, the footprint of the meter is less than that for a (comparable feed rate) weigh feeder. Another important issue is proper selection of the rotary valve as the operation of the meter is highly dependent on proper selection of the rotary valve. Also, a delumper may have to be used. The following are some important issues:

1. **Accuracy:** it can provide an accuracy of 0.5% AR of the selected feed rate through proper regulation. A high-resolution feeding principle is crucial for measurement accuracy.
2. **Control and computing unit:** As indicated in Fig. VIII/7.4.0-1, there will be an intelligent computing and controlling unit to provide a user-friendly operator interface and communication facilities along with necessary controls and feed rate and totalized outputs. Also, it can provide good self-diagnostic features.
3. **Limited vendors:** Since this type of instrument is mainly used for dedicated services, available manufacturers are limited.
4. **Range:** In plastics processing operations, weigh meter feeding is typically best suited to the high rate.
5. **Tare check:** As there is a chance of drift of tare weight, it is important that the tare weight is rechecked and zeroing is done periodically.
6. **Material containment:** The weigh meter/rotary valve principle ensures complete containment of material.
7. **Vibration:** The system is not prone to external vibration and there is isolation.

With this the discussions on force flow weigh meters come to an end and we now explore the details about the process batch weigher.

8.0.0 PROCESS BATCH WEIGHER

The process batch weigher or in-process weigher is used in a wide range of industrial applications including for grain, powder, flour, cement, fertilizers, plastics, etc. The major functional areas are listed here:

- Monitoring and control;
- Blending;
- Display of flow rate and totalizing;
- Bulk outloading and batching.

Vibrating wire load cell: These are used in force flow solid flow measurement. Vibration load cells are mainly used for tie back or rock belt. It is also used for monitoring loads in steel struts tunnel support. There are 3–6 vibrating steel wire strain sensor mounted parallel to the longitudinal axis equidistant around the circumference. These are manufactured from tensile heat treated and stress relieved steel with precision bearing surface. The load cell gives stability of measurement for a long period.

FIGURE VIII/7.4.0-2 Vibrating wire load cell.

8.1.0 Basic Principles Outline of Process Batch Weighers

Basically there are two parts: one is the basic weigher and the other is the associated controller. The process weigh batcher is ideally suited to continuous weigh batching systems as found with bagging type systems and process weighing systems. There are inputs from upstream and downstream processes for interlocking. Material gate closing times can be controlled by adjustable delays or with proximity switch inputs. With design variation there can be a number of types of machines, such as a bag filling machine with stitching and conveying, a cement/sugar bagging machine, granule bag filling machine, soap stone powder packing machine, water-soluble fertilizer packing machine, etc. Some typical process weighers are depicted in Fig. VIII/1.0.1-2.

8.2.0 Automated Process Batch Weighing Process

In many plants for batch-blend bulk products, weigh batching is done manually. Such a manual process is not only time-consuming but it may have an effect on product quality as well as loss of materials. An automated weigh batching system has become an invaluable system to increase productivity, give more accurate measurement of ingredients resulting in better product quality, minimize product loss and dust, and reduce the cost of materials purchased. There are two automated weigh batching methods: as gain-in-weight and loss-in-weight methods.

8.2.1 GAIN-IN-WEIGHT METHOD

In this method, batch ingredients are generally conveyed in sequence into a hopper located above a process vessel. The receiving vessel can be a hopper positioned above a blender, reactor, or other process equipment, or it can be the equipment itself. With the initiation of a batch sequence, by manual push button or by an automated signal, the controller is programmed to activate the first mechanical conveyor or rotary airlock valve to begin loading the first ingredient into the receiving vessel at the maximum feed rate. The hopper is fitted with a set of load cells that weigh the material and transmit weight-gain data to the controller (which may be an intelligent control system such as PLC). Based on the load cell weight gain data, the controller regulates or lowers the feed rate. While discussing gain-in-weight mode, another variable "material-in-flight" must be accounted for. Material-in-flight represents the amount of material still on its way to the scale after the batch controller has deactivated the material feed device. For this reason, it may be necessary to lower the feed rate (we have a similar experience when filling petrol/gasoline into a car at a fuel station) prior to reaching the target weight, i.e., when the target is very close. The controller stops the mechanical conveyor or rotary airlock valve at a preset amount before the target weight is reached to compensate for material-in-flight. As soon as the preset weight is reached then the system stops. Similarly if there be any other ingredient same will be fed. Finally, the controller automatically charges the batch.

8.2.2 LOSS-IN-WEIGHT METHOD

This method has been discussed at length and so is not discussed in detail here. The source of each ingredient is mounted onto load cells for weighing and transmitting weight loss data to a controller to regulate starting and stopping of conveyors.

Determining the most suitable weigh batching method can depend on the process involved, e.g., if the material is delivered in rail cars or bulk trucks and stored in silos, the loss-in-weight method is not a practical solution and the gain-in-weight method should be adapted. Conversely, when material is received in bulk bags, a loss-of-weight system would obviously give a better and simpler solution. Integrating bulk bag unloaders mounted on load cells may offer a simple solution.

An automated weigh batching system is often integrated with the plant's bulk handling system, with pneumatic and/or mechanical conveyors. All upstream and downstream equipment, from receiving to processing or packaging, can be sealed to eliminate contamination of the product and the plant environment. The process weigher and various bagging/packaging machines vary greatly and are normally developed for specific plants and specific units.

8.3.0 Controllers of Process Batch Weighers

Controllers for process weigh batchers are normally meant for continuous weigh batching systems as found in process weighing and/or with bagging systems. The controllers can totalize the material throughput, and can be made to automatically (manually at any position) stop after a preset number of batches or preset weight. There are other displays, such as displays of the total weight bagged, the bagging rate, or the current bag weight, etc. These controllers are intelligent programmable digital controllers, and can be programmed for the desired function. The main functional applications for process weighing controllers are material totalizing, batching out a preset weight of material, flow rate measurement, and flow rate control. Time outs can be set on motion detection and failure to dump to ensure a system stall does not occur. Filling time out makes sure the tail end of a batch is totalized. It is possible to set the speed of the filling systems. Most of these controllers are provided with automatic in-flight compensation (programmable). These controllers can accept various analog/digital inputs to carry out interlock functions with upstream and downstream devices as already discussed. They can generate an alarm output also. These will be in addition to normal analog output (4−20 mADC), PLC/DCS/PC interface through RS232 or RS422or RS485 with suitable protocol such as MODBUS protocol, for example. There will be 2−4 lines backlit LCD or LED displays and keys for the operator interface. These are normally suitable for panel mounting but withstand harsh plant environment so that they can be used in a local panel.

With this, the discussions on solid flow measurement methods come to an end and we now look into the details of the various accessories necessary for solid flow measurement.

9.0.0 CONCLUDING DISCUSSIONS ON SOLID FLOW MEASURING SYSTEMS

Readers by now will understood that in most of cases when the mass flow of solids is measured that the gravimetric method of measurement is much better and more accurate as compared with volumetric measurement. In this section solid flow measurement issues have been summed up. Therefore, in gravimetric measurement it is necessary to measure weight. The weight measurement role of load cells cannot be overestimated. Similarly, the speed of conveying systems plays a great role in completing the measurements. Also, speed sensing is responsible for controlling the speed of the drive for the various conveyors through which materials are conveyed. Motor speed control in certain cases, where the set feed rate is necessary, is an important issue. Apart from that there is the

necessity for various other accessories for proper operation of conveyors, e.g., sway switch and zero speed switch. In this section these will be covered.

9.1.0 Load Cell

As we have already seen in previous sections, load cells and associated electronics are not only used in belt scales and weigh feeders, but in many other applications. Since load cells have been discussed at length in Section 4.3.0 they are not described again here. For load cells and associated electronics Section 4.3.0 may be referenced.

9.2.0 Speed Sensor

As we have already seen in previous sections, speed sensors and the associated electronics are not only used in belt scales and weigh feeders, but in many other applications. Since speed sensors and associated electronics have been discussed at length in Section 4.4.0 they are not described here. For load cells and associated electronics, Section 4.4.0 may be referenced.

9.3.0 Motor Control

The motor control system is not only used in weigh feeders, but in many other applications. Since the basic motor control system and associated electronics have been discussed at length in Section 4.6.0 they are not described here. For load cells and associated electronics, Section 4.6.0 may be referenced.

9.4.0 Conveyor Accessories

These have been covered at length in Section 4.7.0, so for details regarding these, Section 4.7.0 may be referenced.

With this, the discussion on solid flow measurement is concluded. As indicated earlier, it is worth noting that pneumatic conveying of solid material is quite popular in certain industries. This is an example of two-phase flow measurement. In connection with ***two-phase flow measurement*** *further details are available in Section 1.2.0 of Chapter IX*. So, for complete details, the reader is advised to go through that section. We now look into the details regarding multiphase flow often encountered

LIST OF ABBREVIATIONS

ABS Absolute
AC Alternating current
ADC Analog to digital converter
AR Actual reading (in connection with accuracy)
BHP British horse power/bottom hole pressure
CCW(/CW) Counterclockwise (/clockwise)
CEMA Conveyor Equipment Manufacturer Association
CFBC Circulating fluidized bed combustion
CMRR Common mode rejection ratio
CMV Common mode voltage
CS Carbon steel
DC Direct current
DCS Digital control system
DI Ductile iron
DP Differential pressure
DPT Differential pressure transmitter/transducer
DSP Digital signal processing
EMC Electromagnetic compatibility
ESP Electrostatic precipitator
FC Fail to close (for valve)
FGD Flue gas desulfurization
FO Fail to open (for valve)
FRP Fiber glass reinforced plastic (thermowetting)
FSD Full-scale division (in connection with accuracy)
HVAC Heating ventilation and air conditioning
IC Integrated chip/internal combustion (engine)
ID Internal diameter
I/O Input/output
IS Intrinsic safety
LC Load cell
LCD Liquid crystal display
LED Light-emitting diode
LHS Left-hand side
LIW Loss-in-weight
LVDT Linear variable differential transformer
MPE Maximum permissible error
MS Mild steel
MUX Multiplexer
MVT Multivariable transmitter
NB Nominal bore
NIST National Institute of Standards and Technology
NTEP National Type Evaluation Program
OD Outer diameter
PD Positive displacement (meter)
PLC Programmable logic controller
PTFE Polytetrafluoroethylene
PU Processing unit
PVC Polyvinyl chloride
PVT Polyvinyltoluene
RDWR Ratiometric digital weight resolver
RF Raised face/radio frequency
RHS Right-hand side
RPM Revolutions per minute
RTD Resistance temperature detector
SG Strain gage
SIL Safety integrity level
SS Stainless steel
STP Standard temperature and pressure (Fig. I/1.1.2-3)
TC Thermocouple
US Ultrasonic/United States
VDU Visual display unit
VFD Variable-frequency drive
VM Valve manifold
VVVF Variable-voltage variable-frequency
WRT With respect to

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CHAPTER IX

MULTIPHASE FLOW MEASUREMENT

Chapter Outline

1.0.0 INTRODUCTION: CONCEPT OF MULTIPHASE FLOW—AN OVERVIEW

When one listens to the song "Raindrops keep fallin' on my head" we enjoy the song and never think that this is a phenomenon of multiphase (two) flow as rain is falling down through a gas. Similarly, bubbling of gas in soda/lemonade (liquid) or tonic water is an example of multiphase flow. This means that in our everyday life we quite often encounter multiphase flow. However as there is no requirement for any measurement we hardly think about it. This is not the case for the oil and gas industry. During exploration (on/offshore) or production in an oil field it is essential to meter the individual components of oil, water, and gas stream. This is important for custody transfer, pricing, and finding ways and means for economic operation of production facilities. Multiphase flows are not only experienced in oil and gas industries, they are seen in many other industries, such as the food and drink, chemical, and pharmaceutical industries etc. to name a few. From basic physics it is well known that the phase is defined as one of the states of matter. Therefore, the phase can be a solid, a liquid, or a gas. In the simplest terms, multiphase flow is the simultaneous flow of several phases. In that sense when we refer to multiphase flow in oil and gas areas meaning flow of gas, oil, and water this is a misnomer as in this phase the oil and water are both liquids. Therefore, we should correct ourselves by referring to multiphase flow as the flow of materials

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consisting of more than one phase or multicomponents. There are two things that should be noted:

- The two components can be of the same phase but these two components should be immiscible, like oil and water.
- In oil and gas exploration there can be as many as four phases, namely, water, crude oil, gas, and sand.

Therefore it is better to look at this from a different perspective. The presence of one or more interfaces varying over space and time renders the hydrodynamics of two-phase flow substantially different from a single phase. The importance of the study of multiphase flow in energy-related industries and applications cannot be overestimated. The simplest case of multiphase flow is two-phase flow. Two-phase flow can be solid–liquid flow (mud, slurries), liquid–liquid flow (two immiscible liquids like oil and water), gas–liquid flow (liquid flow with entrapped gas, e.g., lemonade), and gas–solid flow (pulverized coal flow or any pneumatically conveyed solids). Although two-phase flow is the simplest case of multiphase flow, it has separate importance in industries and is discussed separately.

When Section 3.4.0 of Chapter I is recalled, one finds that measurement of multiphase can be carried out in two ways with the reasoning elaborated below:

- **Conventional single-phase flow meters:** This requires the components/constituents or "phases" of multiphase fluid streams to be separated before measurement by a single-phase flow meter, i.e., separation of multiphase fluid streams upstream of the point of measurement. Such single-phase metering systems normally provide high-performance measurements. However, in the separation method, space and cost will be much higher. Also, the time for analysis will be long, making continuous measurement unlikely. Moreover, accuracy is also moderate at around 5%–10%.
- **Multiphase flow metering (MFM):** Multiphase flow measurement technology is a very attractive alternative, since it may lead to cost savings in the initial installation, i.e., capital cost. There will be time savings in measurement. Also, in the case of oil and gas applications, the measurement of unprocessed well streams takes place very close to the well.

Although modern multiphase meters are available with better performance, it is recommended that before the use of MFMs, due to higher measurement uncertainty, a cost–benefit analysis should be performed over the life cycle of the project to justify its application [1]. Before we move on to discuss the issues at length, we touch upon a few relevant issues in connection with multiphase flow metering. Now let us have a brief overview of fluid mechanics, starting with the historical background of why multiphase flow metering is becoming so important. In the limited volume of the book details on fluid mechanics cannot be explained. For this, if necessary standard book on fluid mechanics may be referenced.

1. **Historical background:** One of the major challenging issue industries have faced for several years is the development of an accurate and reliable multiphase flow measurement system. A multitechnology solution combined with smart data analytics is an option being explored for providing reliable three-phase flow rates to the operator. After long researches since the 1980s, probably around 2006 the first commercial MFM were launched. There had been contributions in research from all parts of the world, so it is not possible to list all the contributors. A few major research institutes whose contributions were tremendous are: Tulsa (US), SINTEF (Norway), Imperial College (UK), National Engineering Laboratory (UK), CMR (Norway), BP, Texaco, Elf, Shell, Agip, and Petrobras. These are only a few, there are several others also. The driving force to develop MFM technology was the forecast decline of production from the major North Sea fields.
2. **Difficulties with multiphase flow metering:** For single-phase flow, it is easier to determine the fluid properties. However, for determination of fluid properties for multiphase measurement it is extremely difficult. In the case of multiphase flow, both compressible and

incompressible fluids will be present in the same pipe at the same time.

- *Energy transfer:* Lack of knowledge of the velocities at a point in the individual phases makes it impossible to give any real picture of the velocity distribution. Normally the gas phase, flows with greater velocity than the liquid, continuously accelerates the liquid, thus involving a transfer of energy. Either phase may be in streamline or turbulent flow. The most important case is that in which both phases are turbulent. When there is no heat transfer to the flowing mixture, the mass rate of flow of each phase will remain substantially constant, however the volumetric flow rates, i.e., velocities, will increase progressively as the gas expands with falling pressure. In the case of evaporation, due to vaporization of the liquid leading to a decreased mass flow rate of liquid and corresponding increase for the vapor, the total mass rate of flow remains constant. As a result, the volumetric flow rate will increase rapidly on account of the combined effects of falling pressure and increasing vapor/liquid ratio. A gas–liquid mixture will have a lower density than the liquid alone.
- *Velocity change:* From the above discussions it is clear that there will be differences in velocities between the constituents. Therefore, when they flow in a vertical pipe in an upward direction, there will be a tendency of the lighter phase to rise more quickly than the denser phase. This will give rise to a slip in velocity (discussed later), as a result there will be changes to the flow pattern, depending on the presence of each of the constituents in the multiphase flow.
- *Fluid properties:* There will be variations in density and viscosity between the two liquids even, e.g., oil and water. Density and viscosity amongst other properties are major influencing factors, along with temperature. In any case the fluid properties of a multiphase mixture cannot be found simply by combining the fluid properties of the individual components. As indicated above, there may be the likelihood that there will be mass transfer between the phases of a multiphase mixture. Multiphase fluid properties really start to get interesting when emulsions form. There is a saying that "oil and water don't mix," but they can when they emulsify. Mayonnaise is an example of this [2]. The point of interest here is that the property of emulsion is totally different from that of the constituents. Such emulsification is possible after mixing of oil with water, making it extremely difficult to measure the flow rate and fluid property.

3. **Multiphase characterizing parameters:** The following parameters are mainly considered as characterizing parameters for multiphase flow. Density and viscosity are not separately described as these will be taken care of with mass flow rate and velocity. The major parameters are:
   - Mass flow and velocity;
   - Temperature;
   - Void fraction;
   - Local void fraction;
   - Critical heat flux;
   - Liquid level and film thickness;
   - Flow regimes;
   - Wall shear stress and turbulence;
   - Velocity distribution.
4. **Factors affecting flow regimes:** The flow structures are classified in flow regimes. The mechanics behind different flow regimes discussed later are affected by the following:
   - *Transient effects:* Transients occur due to the changes in system boundary conditions, i.e., opening/closing of valves.
   - *Geometry effects:* As the name implies, this would occur when there will be changes of inclination or changes in pipe geometry.
   - *Hydrodynamic effects:* The changes in flow regime with no causes of transient or geometrical effects in a horizontal pipe are referred to as hydrodynamic effects, which are mainly

governed by the fluid properties discussed above, i.e., pipe size, flow rate, etc.
- *Combinations of above effects:* Flow regime changes are effected on account of a combination of any of the above effects.

5. **Broad classification of flow regimes:** The determination of flow regimes in pipes in operation is not an easy task and is also dependent on interpretation of the same. However, flow regimes can be classified broadly as follows:
   - *Dispersed flows:* This is characterized by a uniform phase distribution in both the radial and axial directions; i.e., bubble flow and mist flow that are described later.
   - *Intermittent flow:* Intermittent flow is characterized by noncontinuous flow in the axial direction, so, locally unsteady behavior is exhibited, e.g., churn and slug flow.
   - *Separated flow:* In separated flow there will be noncontinuous phase distribution in the radial direction and a continuous phase distribution in the axial direction, i.e., stratified and annular flow.

Here only a brief overview has been presented, with subsequent discussions being more detailed. In the following sections this can be understood easily.

1.1.0 Fundamentals of Multiphase Flow

From the overview discussions, it is clear that there are different characteristics to multiphase flow, depending on the ingredients and their phases in the multiphase. In fact, slurry flow and pneumatically conveyed solid flows discussed in Chapters VII and VIII are also examples of multiphase flow. The following are a few examples of multiphase flow:

1. **Two-phase flow:** There can be combinations of flow of ingredients in two phases (or maybe in immiscible liquids, i.e., liquid—liquid) such as:
   - *Gas—solid flow:* Pneumatically conveyed solids when solid particles are suspended in gas. Pulverized coal flow in a fossil fuel plant or flow of raw materials preheated in a cement plant are examples.
   - *Gas—liquid:* This form of multiphase is very commonly found in industrial applications. Flow in tonic water and lemonade is a very common example, but it is also found in oil and gas.
   - *Liquid—solid:* When solids are conveyed hydraulically these are commonly found; such as sewerage, river flow, hydrocyclone.
   - *Liquid—liquid:* This is in its true sense not two phases but two liquids in immiscible form, such as oil—water or salad dressing (oil + water).
2. **Multiphase flow:** These flows also have practical applications in industries, Such as the following:
   - *Gas—liquid—solid:* These are found in froth flotation in mining and mineral beneficiation processes.
   - *Gas—liquid—liquid flow:* This is the most common form of material coming out from a well in oil exploration, such as natural gas, oil, and water.
   - *Liquid—liquid—solid:* This can occur when sands are mixed with oil.
   - *Four-phase flow:* This occurs in oil and gas exploration, when sand is also present with oil, in fact, a shale shaker is used to separate large solids in the drilling operation.
3. **Features required for multiphase flow meters (MFM):** Although there are many uses of multiphase flow meters in other industries, it is the oil and gas industries from where the need for MFM was first felt. The requirements for MFM have been discussed in Section 1.0.0. Unfortunately there is no single meter by which MFM can be realized. Therefore, a multiphase flow metering system is developed taking care of at least any two technologies discussed in Section 3.4.3 of Chapter I. In spite of uncertainty associated with MFM, the following are expected.
   - Good repeatability and accuracy of the measurement system;
   - Coverage of wide flow rate and phase fraction for fluids with varying fluid properties;
   - Easy installation and interpretation;

- Lower capital expenditure;
- Acceptance by appropriate authorities for custody transfer.

4. **Measurement categorizations:** Various MFM based on technologies discussed in Section 3.4.3 of Chapter I can be made on the basis of measurement of elemental analysis: concentration and velocity of individual atomic species [3], mass, density, velocity, and momentum.
5. **Kinds of flow:** There are three categories of multiphase flow:
   - *Steady flow:* In steady flow through a conduit, pressure and corresponding velocity may vary with the location of the same in the pipe but not with time;
   - *Transient flow:* When pressure/velocity change with time;
   - *Pseudosteady flow:* Pressure, velocity, and phase fraction may vary with time, however such variation with time is constant.

Before we discuss multiphase flow metering in detail, we define some basic terms, so that the details can be easily explained and understood.

1.1.1 TERMS AND DEFINITIONS

We define a few terms that are frequently encountered in multiphase flow metering. The major terms are as elaborated in Table IX/1.1.1-1. Some of the various terms discussed in Table IX/1.1.1-1 have been explained in Fig. IX/1.1.1-1. This figure should be read in conjunction with Table IX/1.1.1-1. All these will be used frequently later in the chapter. Therefore it is very important to go through these.

TABLE IX/1.1.1-1 Commonly Used Terms and Definitions (Multiphase Flow Measurement)

Term	Definition and Explanation
Adjustment [1]	Operation of bringing a measuring instrument into a state of performance suitable for use (ISO-VIM, 1993). Adjustment should never be confused with calibration nor with verification of calibration
Calibration [1]	Set of operations that establish under specified condition, the relationship between values of quantities indicated by a measuring instrument or measuring systems, or values represented by a material measure or certified reference material, and the corresponding values realized by standards. The result of calibration may call for adjustment
Certified reference material (CRM) [1]	Reference material, accompanied by a certificate, one or more of whose property values are certified by a procedure which establishes traceability to an accurate realization of the unit in which the property values are expressed and for which each certified value is accompanied by an uncertainty at a state level of confidence (ISO-VIM, 1993)
Disperse flow	Refer to Subsection 1.0.0.5
Dry gas	Gas containing no liquid under actual operating conditions. At different conditions (pressure/temperature) liquid may fall
Dryness fraction	This represents the ratio of mass flow rate of gas and total mass flow rate. If q_{mg} is the mass flow rate of gas and q_{ml} is the mass flow rate of liquid then dryness fraction x is given by: $$x = (q_{mg})/(q_{mg} + q_{ml})$$
Emulsion	A fine dispersion of minute droplets of one liquid in another in which it is not soluble or miscible. In connection with multiphase flow measurement it is worth noting that emulsions of oil in water and water in oil offer different properties when permittivity measurement is done
Entrained water	Water suspended in oil including emulsion but not dissolved/free water

Continued

TABLE IX/1.1.1-1 Commonly Used Terms and Definitions (Multiphase Flow Measurement)—cont'd

Term	Definition and Explanation
Fiscal	Fiscal may refer to meter's service which may not be according to any standard. A fiscal and for that matter custody transfer is a basis for money transfer between two agencies
Flow regime	Depending on the Reynolds number, a single-phase flow can be categorized as a laminar or turbulent flow regime. Flow regime refers to the physical geometry exhibited by multiphase flow in a pipe. So, in multiphase flow measurement, a particular type of geometric distribution of constituents is referred to as *flow regime/flow pattern*
Gas—liquid ratio (GLR)	Under the same pressure and temperature conditions, the volume flow rate ratio of gas to total liquid is referred to as GLR. If q_g, q_o, and q_w are volume flow rate of gas, oil, and water, respectively, then $GLR = q_g/(q_o + q_w)$ (unitless)
Gas—oil ratio (GOR)	Under the same pressure and temperature conditions (STP), the volume flow rate ratio of gas to oil is referred to as GLR. If, q_g and q_o are the volume flow rate of gas and oil, respectively, then $GLR = q_g/q_o$ (unitless)
Gas void fraction	This is a ratio which refers to the cross-sectional area. It represents the fraction of the total cross-sectional area occupied by gas (the same for a liquid is the *hold up* area). Refer to phase fraction area also. For this refer to Fig. IX/1.1.1-1 (Fig. B) and the explanation below it. Gas void fraction represented is by λ_g (also represented by ε_g or e_g)
Gas volume fraction (GVF) (α_g)	Under the operating condition of the section, the ratio of volume flow rate of gas and total multiphase volume flow rate is referred to as the gas volume fraction—normally expressed in % fraction. It stands for $GVF = q_g/(q_o + q_w + q_g)$. It should not be confused with gas void fraction. While the former is based on the flow rate, the latter is based on the area. Since gas velocity is high it may so happen that 75% of gas void fraction could be 95% of gas void fraction. This is related with the volume flow rate as explained in expression 2 of Fig. IX/1.1.1-1. It is represented by α_g and α_l for gas and liquid, respectively [*liquid volume fraction* $\alpha_l = (q_o + q_w)/(q_o + q_w + q_g)$]
Hold up area	This refers to the fraction of total cross-sectional area occupied by liquid (cross-sectional area). For this refer to Fig. IX/1.1.1-1 (Fig. B) and the explanation below it. Refer to phase fraction area also. It is represented by λ_{liquid}
Homogeneous flow	In a homogeneous flow pertinent to multiphase flow, all phases are evenly distributed over the cross-sectional area of the closed conduit. Here there are two interesting things. These are that the composition is the same at all points and velocity of all phases are the same—hence there is no slip as shown in E of Fig. IX/1.1.1-1. Refer to expressions 3 and 4 of Fig. IX/1.1.1-1, k = 1, and GVF = e_g (=1-ε_g)
	Homogeneous oil—water flow: This is a corollary to the above applicable for two-phase flow involving water and oil. In that case, oil and water are uniformly distributed, i.e., the composition is the same at all points within the closed conduit
Intermittent flow	Refer to Subsection 1.0.0.5
Inversion region	The inversion region lies between oil-continuous and water-continuous flow defined below in this table. It is unpredictable and can switch between the two from one moment to the next. Naturally operating in the oil/water inversion region is very difficult for certain multiphase measurement. Refer to F and 6 in Fig. IX/1.1.1-1

Continued

TABLE IX/1.1.1-1 Commonly Used Terms and Definitions (Multiphase Flow Measurement)—cont'd

Term	Definition and Explanation
Liquid–gas ratio (LGR)	Under the operating condition of the section, the ratio of volume flow rate of liquid and total gas volume flow rate is referred to as the liquid–gas ratio—normally expressed as volume/volume. $LGR = (q_o + q_w)/q_g$
Liquid volume fraction (LVF)	Under the operating condition of the section, the ratio of volume flow rate of liquid and total multiphase volume flow rate is referred to as the liquid volume fraction—normally expressed in % fraction. It stands for $LVF = (q_o + q_w)/(q_o + q_w + q_g)$
	Or, $LVF = 1 - q_g/(q_o + q_w + q_g)$ or, 1-GVF
Lockhart-Martinelli number/parameter	Lockhart-Martinelli number/parameter (LM or X) is the ratio of Froude number (defined in Subsection 1.0.1.1 of Chapter III) of liquid to that of gas. Fig. I/3.4.2.4-1 may be referred to for a detailed explanation
Mass flux	Mass flux gives the mass flow per unit area. If A is the cross-sectional area of conduit and q_m is the mass flow rate then $$\text{Mass flux} = q_m/A$$
Mean density	Mean density of multiphase flow ($\overline{\rho}$) is related to gas void fraction and mean density of gas and liquid with the Eq. IX/1.1.1-1 $$\overline{\rho} = 1 - \varepsilon_g(\text{or } e_g)\rho_g + (1 - 1 - \varepsilon_g)\rho_l \qquad \text{(IX/1.1.1-1)}$$
	So, if MFM measures the local mean density then using phase densities, 1-εg could be found and from that GVF can be obtained knowing K (refer to Fig. IX/1.1.1-1)
Multiphase flow meter	A measuring system, including possible conditioning unit, used for measuring the individual constituent flow rates in a multiphase flow. The system may consist of instruments/devices for measuring the composition and velocities. Note that under this definition also a conventional two- or three-phase test separator is a multiphase meter
Multiphase flow velocity	As usual it is the ratio of the multiphase volume flow rate and the cross-sectional area of the conduit (i.e., volume rate divided by area gives velocity). It is worth noting that only in homogeneous flow without slip is this velocity a meaningful value. Multiphase flow velocity is the sum of gas superficial and liquid superficial velocity
Multiphase fraction meter	A system of measuring the phase area fractions of constituents of a multiphase flow through a cross-section of a conduit
Oil volume fraction (OVF)	Under the operating condition of the section, the ratio of volume flow rate of oil and total multiphase volume flow rate is referred to as the oil volume fraction, normally expressed in % fraction
	$OVF = q_o/(q_o + q_w + q_g)$
Oil-continuous two-phase flow	This is a two-phase flow of oil/water characterized in that the water is present and distributed as droplets surrounded by oil, the mixture acts as an insulator. This is shown in F in Fig. IX/1.1.1-1
Phase	In physics normally phase refers to the state of matter. In multiphase flow the same is used to refer to a constituent
Phase area fraction	This refers to the fraction of the cross-sectional area of the conduit occupied by one of the phases (constituents) in a multiphase flow, at the same local position
Phase flow rate	Amount of flow of one constituent/phase through the cross-section of a conduit. It can be volumetric or mass flow rate

Continued

TABLE IX/1.1.1-1 Commonly Used Terms and Definitions (Multiphase Flow Measurement)—cont'd

Term	Definition and Explanation
Phase mass fraction	This represents the fraction of total mass flow rates of multiphase mass flow, delivered by a phase mass flow rate of one of the constituents. If q_{mg} and q_{mw} are the mass flow rate of gas, oil and water respectively then phase mass fraction $$f(\text{say gas}) = q_{mg}/(q_{mg} + q_{mo} + q_{mw}) \quad \text{(IX/1.1.1-2)}$$
Phase mass fraction	This represents the fraction of total volume flow rates of multiphase volume flow, delivered by a phase volume flow rate of one of the constituents. If q_g, q_o, and q_w are volume flow rate of gas, oil, and water, respectively, then phase volume fraction $$f_m(\text{say gas}) = q_g/(q_g + q_o + q_w) \quad \text{(IX/1.1.1-3)}$$
Salinity	Salinity refers to the amount of dissolved salts that are present in water (kg/m^3)
Separated flow	Refer to Subsection 1.0.0.5
Slip	This represents the flow condition in a multiphase flow, when the velocities of liquid and gas in the cross-section in a conduit are different. Slip denotes the difference of velocities of gas and liquid as shown in 3 in Fig. IX/1.1.1-1
	So, slip [also known ***phase slip***] $= v_g - v_l$
Slip ratio K	Slip ratio or phase slip ratio is the ratio of velocity of gas phase to velocity of liquid phase as shown in 3 in Fig. IX/1.1.1-1. $K = v_g/v_l$
Superficial phase velocity	The flow velocity of one phase of a multiphase flow, assuming that the phase occupies the whole conduit by itself. It may also be defined by the relationship (phase volume flow rate)/(pipe cross-section). Compare with multiphase flow velocity. When q_g and q_l are volumetric throughput for gas and liquid, respectively, and cross-sectional area of the conduit is A. Then, superficial velocity for gas and liquid is represented, respectively, by v_{sg} and v_{sl} given by: $$v_{sg} = q_g/A \text{ and } v_{sl} = q_l/A:$$ *When the above equation is compared with mass flux one will notice these are very similar. So people often name superficial velocity as volume flux.* $$v_{multiphase} = v_{sg} + v_{sl} \quad \text{(IX/1.1.1-4)}$$
Void fraction	This represents the ratio of local cross-sectional area in a conduit occupied by gas phase and the total cross-sectional area of the (same) conduit. As shown in Fig. IX/1.1.1-1
Volume flow rate	Under the prevailing condition in the section, the volume of fluid flowing through the cross-section of a conduit in unit time
Water-continuous two-phase flow	This is a two-phase flow of oil/water characterized in that the oil is present and distributed as droplets surrounded by water, the mixture acts as an insulator. This is shown in F in Fig. IX/1.1.1-1
Water cut	Under the same operating condition, the ratio of water volume flow rate, and the total liquid volume flow rate (oil and water) is referred to as water cut. The WC is normally expressed as a percentage

Continued

TABLE IX/1.1.1-1 Commonly Used Terms and Definitions (Multiphase Flow Measurement)—cont'd

Term	Definition and Explanation
Water fraction meter (WFM)	A device for measuring the phase area fractions of oil and water of a two-phase oil/water flow through a cross-section of a conduit. This is expressed as a percentage
Water-in-liquid ratio (WLR)	Under the same operating condition, the ratio of volume flow rate of water and total liquid, i.e., $WLR = q_w/(q_w + q_o)$
Water volume fraction (WVF)	Under the operating condition of the section, the ratio of volume flow rate of water and total multiphase volume flow rate is referred to as the water volume fraction, normally expressed in % fraction. $WVF = q_w/(q_o + q_w + q_g)$
Wet gas [1]	Gas that contains liquids, generally wet gas is defined as gas/liquid systems with a Lockhart-Martinelli parameter smaller than approximately 0.3. Hydrocarbon gases that contain heavy components that will condensate during further processing (but at a particular P and T behaves as a pure gas) are not considered to be a wet gas from a measurement point of view

1.1.2 MULTIPHASE FLOW CLASSIFICATION AND REGIMES

From the previous discussions we have come across many terms, all of which have importance, but the gas volume fraction (GVF) is extremely important. The change of state there will be a number of changes in physical parameters, such as density and viscosity, which is extremely important in the study of flow. Therefore, the importance of GVF in classifying multiphase flow cannot be overestimated. With variations in GVF the content of gas to liquid varies. Naturally the type of measurement suitable for each case can be different. MFMs can be classified in terms of gas volume rate, i.e., according to the GVF. Such classification is well justified because any multiphase flow measurement with a wet gas meter, which mainly measures gas flow with traces of gas, will be absolutely different for a meter measuring oil rather than liquid flow with traces of gas. So, in order to make such a classification, GVF has been divided into four classes: low, medium or moderate, high, and very high GVF. Naturally, any fluid in low GVF would have very low traces of gas, with mainly liquid material. On the other hand, multiphase with very high GVF is actually wet gas, i.e., mainly gas with traces of liquid. A detailed classification of multiphase fluid according to GVF % has been elaborated in Table IX/1.1.2-1, with a detailed explanation.

Having understood the reason for multiphase classification, it is time to study the characteristic features of multiphase flow and various flow regimes in multiphase flow.

1.1.3 MULTIPHASE CHARACTERISTICS AND FLOW REGIMES

In single-phase flow, there are mainly (transition not considered) two regimes: laminar or turbulent flow. In multiphase flow things are a little more complicated. The major reason for such complication can be attributed to the dependence of fluid mechanics distribution and topology of the components within multiphase fluid flow. Large variations in density and viscosity are responsible for the behavioral difference of two-phase flow of, e.g., solid—gas with that of solid—liquid mixtures. It is important to understand the nature

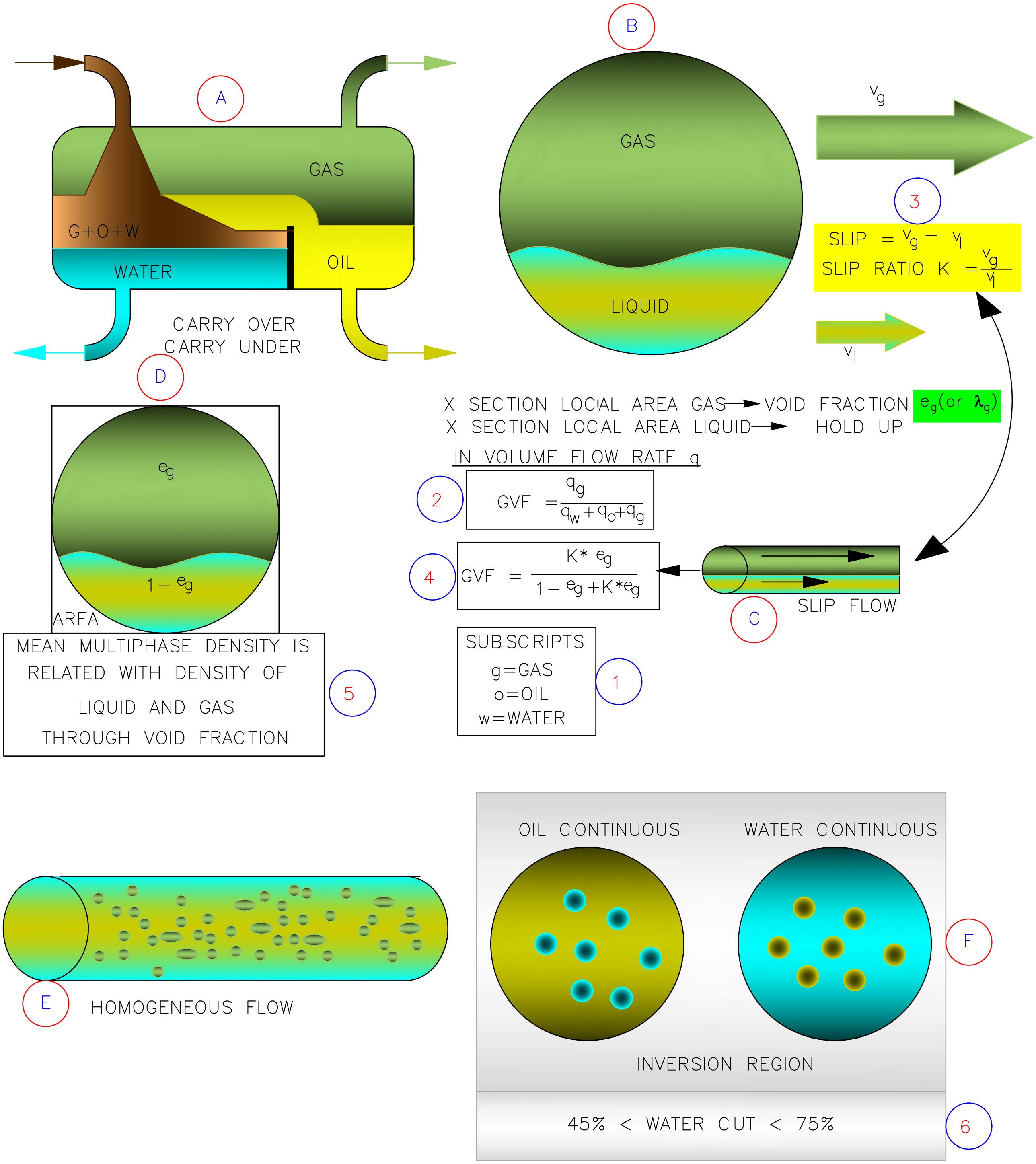


FIGURE IX/1.1.1-1 Explanation of terms MFM. All explanations given here are related to Table IX/1.1.1-1. Hence it is to be read in conjunction with the table only. *Developed based on an idea from E. Graham, Introduction to multiphase and wet gas flow, National Measurement System, NEL. http://www.tuvnel.com/assets/content_images/Intro%20to%20Muph%20and%20wet%20gas.pdf.*

TABLE IX/1.1.2-1 Multiphase Flow Metering Classification

GVF Classification	GVF Ranges (%)	Discussions
Low GVF	0 to <25	Mainly liquid with traces of gas, so gassy liquid material. Simple type of single-phase meters at times would suffice, but uncertainty of measurement creeps in with increase in percentage value of GVF
Moderate GVF	25 to <85	In this range simple single-phase measurement will not function. So, MFMs are to be deployed. Also it is observed that in this range MFMs give the best performance
High GVF	85 to <95	At the initial stage of discussions it has been stated that there are uncertainties in MFMs and the same increase with an increase in the GVF value. With an increase in GVF the complexities increase and uncertainty will increase as the relative proportion of the fraction of the component of highest value (in this case the oil) decreases [1]. If complexity is too high it is better to use partial separation so as to bring GVF in the moderate range for better performance in measurement
High GVF	85 to 100	The top end of GVF is termed wet gas. In the lower end of GVF in-line MFMs can be used as describe above. However, at the higher end of this range wet gas meters discussed later would be used

of the interactions between the phases and how these influence the flow patterns and how to predict pressure drop dependent on flow pattern, the relative velocity of the phases (slip velocity and hold up). Therefore, attention should be on the following:

- The flow patterns;
- The hold-up of the individual phases and their relative velocities;
- The relationship between pressure gradient in a pipe and the flow rates and physical properties of the phases.

The component distribution within the conduit varies depending on the superficial velocities of the phases and the orientation of the pipe. Thus, in multiphase flow, the mass, momentum, and energy transfer processes and transfer rates are very sensitive to the geometric distribution of various components in the conduit during multiphase flow, i.e., topology or configuration. Complications in multiphase flow come from two-way coupling between the flow in each of the phases or components, the geometry of the flow, and the changes (rate change) of that geometry. So, the study of flow pattern or geometric distribution can be the starting point for further investigations. If simple flows in vertical or horizontal pipes are considered, then one would find that there exist many ways to relate various flow patterns with component volume fluxes (jA, jB), on volume fraction and on the fluid properties such as density, viscosity, and surface tension. From such attempts we get are results of various investigators in this complex area. Out of many contributors, the works of Baker (1954), Schicht (1969), Wallis (1969), Weisman (1983), and Weisman and Kang (1981) are worth noting and one should be thankful to them for establishing some basis of investigations and analysis. From this one can infer that there is still a necessity for extensive research to establish a suitable design basis for the establishment of a generalized flow regime through proper understanding of flow patterns in multiphase flow. Therefore, the majority of the

data available are from studying the literature. First let us investigate various issues involved in establishing a flow regime for multiphase flow.

1. **Unpredictability for flow regime:** The flow regime map identifies the flow patterns occurring in various parts of a parameter space defined by the component flow rates in terms of volume fluxes, mass fluxes, momentum fluxes, or other similar quantities. The establishment of a flow regime in multiphase flow is more difficult than in single-phase flow. The establishment of any generalized map is difficult mainly on account of the following issues.
   - *Dimensional:* Multiphase flow maps are mostly dimensional, and applicable to the specific pipe sizes and fluids.
   - *Transitions:* There are several transitions in many flow pattern maps and the corresponding instabilities are governed by different sets of fluid *properties*.
   - In single-phase flow, there is an established upstream straight length necessary to establish fully developed turbulent pipe flow. The upstream straight lengths for multiphase flow are less, but it is quite possible that some of them are for temporary or developing flow patterns [4].
   - *Nonunique flow pattern:* There is a presumption that there exists a unique flow pattern for given fluids with given flow rates. It is by no means certain that this is the case [4].
2. **Requirement flow pattern study:** As indicated earlier, multiphase flow measurement depends on the rate of exchange of mass, momentum, and energy between different phases. These physical parameter exchanges (referenced above) between phases, as well as between any multiphase mixture, and the external boundaries depend on these internal flow *geometries* and *interface* area. Therefore, for multiphase flow measurements study of the flow regime is very important. The heat transfer and pressure drop characteristics are different in bubble flow and annular flow, for example. However, the *central task* is to predict which flow pattern will exist under any set of operating conditions as well as to predict the value of characteristic fluid and flow parameters [5].
3. **Slurry flow regime:** Basically, slurry flow, discussed in Chapter VII, is also a multiphase flow. There are a few flow regimes for slurry multiphase flow. These are homogeneous/heterogeneous flow and saltation flow. The slurry flow regime is another very important issue in multiphase flow metering and needs separate discussions for its characteristics. In this book, Chapter VII has been dedicated to the same. Various types of flows discussed here have already been discussed at length in Sections 2.1.1, 2.2.1, and 2.2.2 of Chapter VII and are described in Fig. VII/2.2.0-2, hence they are not repeated here. We now take the flow through simple pipes. The discussion starts with vertical pipe flow.

   In gas–liquid interface flow, when a plane is normal to the axis of the conduit it will probably cut many interfaces. However, such interfaces and the distribution fall into a number of characteristic patterns which can be interpreted from the independent variables of the system. In the next section attempts will be made to do this.
4. **Vertical pipe flow regime:** In vertical flows, with an *increase* in the superficial gas velocity the multiphase flow will change between all phases, i.e., (from the left), bubble, slug, churn, annular, etc., as depicted in Fig. IX/1.1.3-1A. These different kinds of such patterns/flow regimes can be seen clearly in the figure.
   - *Bubble flow:* This consist of a continuous liquid phase with the gas phase distributed in discrete bubbles within a liquid continuum. Nonuniform sizes of bubbles travel with complex motion and coalesce. These are found mainly at the center of the conduit, and also near pipe walls. At lower velocity small bubbles are generated at gas distributors or for nucleate boiling.

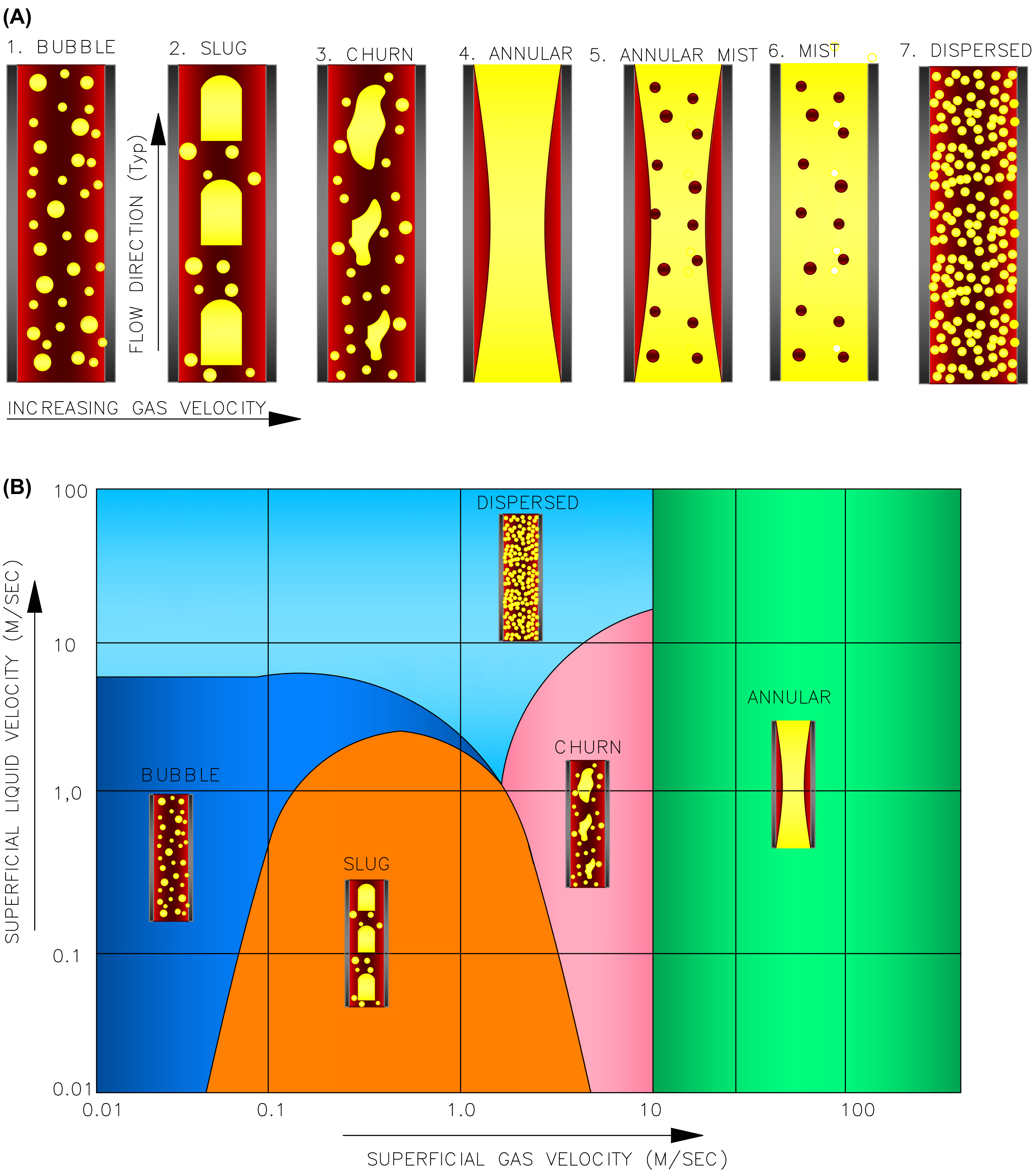


FIGURE IX/1.1.3-1 Vertical pipe flow regimes and flow map. (A) Vertical pipe flow regime. (B) Vertical pipe flow map.

- *Slug:* When the concentration of bubbles in the bubble flow becomes high, bubble coalescence occurs and the bubble diameter approaches that of the tube. With this, bullet-shaped (enlarged) bubbles the slug-flow (or plug-flow) regime is reached. These are often referred to as Taylor bubbles. Taylor bubbles are surrounded by a thin liquid film and some smaller bubbles.
- *Churn:* With increased gas flow, the velocity of the bubbles will also increase, causing breakdown of these bubbles. Such condition leads to an unstable regime in which there will be an oscillatory motion of the liquid upwards and downwards in the conduit. On account of this churning motion in the conduit it is named *churned* flow. Churn flow, with its characteristic oscillation, often covers a wide range of gas flow rates. This happens mainly in wider conduits, but in the case of narrow-bore tubes the oscillations may not occur and there will be a smoother transition between slug flow and annular flow. Churn and slug flow patterns are often grouped as intermittent flow regime and show large fluctuations in void fractions and pressure drops.
- *Annular:* In annular flow, the liquid flows on the wall of the tube as a film and the gas phase flows in the center. Usually, some liquid phase is entrained as small droplets in the gas core. In the case of heat transfer systems the wall may be too hot to have any liquid film.
- *Annular mist and wispy annular:* This is basically annular flow but with liquid droplets at the center gas core. With an increase in liquid flow, the concentration of droplets in the gas core increases and coalescence of droplets occurs, leading to large lumps or streaks, as wispy liquid occurring in the gas core. This is identified as wispy annular flow.
- *Dispersed flow:* At higher velocities bubbles can be formed due to the breakup of larger bubbles and flow occurs as liquid with fine bubbles of gas.
- *Downward flow:* Discussions made so far for upward direction of flow as shown in Fig. IX/1.1.3-1A. Downward flow pattern studies are similar to what has been described above, only the flow patterns occur at *different* ranges of flow.

We now look into the details of the horizontal pipe flow regime.

5. **Horizontal flow:** Force *gravity* is mainly responsible for the complications of the horizontal multiphase flow regime. This force attracts a liquid phase towards the bottom and following variations in horizontal flow, regimes are observed and these have been depicted in Fig. IX/1.1.3-2A.
   - *Stratified plane:* Gravitational spread is complete, so liquid flows along the bottom of the conduit with gas flowing along the top part of it with a smooth interface, and so fluids are stratified. The typical velocity range is liquid <0.15 m/s and vapor $0.6-3$ m/s.
   - *Stratified wavy:* This is also a stratified pattern, but on account of the higher gas velocity, large surface waves are formed on the gas−liquid interface, creating a stratified wavy flow regime. The typical velocity range is liquid <0.3 m/s and vapor >5 m/s.
   - *Plug:* Like in vertical pipes, here also the plug flow regime is characterized by somewhat (larger) bullet-shaped bubbles traveling along the top of the conduit. This is an intermittent flow type. The typical velocity range is liquid ~ 0.6 m/s and vapor <1.0 m/s.
   - *Slug:* Like the plug type, this is also an intermittent type flow regime. Bubbles are bigger and also the liquid contains smaller bubbles.
   - *Bubble flow:* The bubbles normally tend to flow at the top of the tube, unless there is high turbulence to disperse them. The typical velocity range is liquid $1.5-5$ m/s and vapor $0.3-3$ m/s.
   - *Annular:* This has a continuous gas core with a complete wall liquid film. When the gas velocity increases further the slugs are pierced with a gas core and the flow

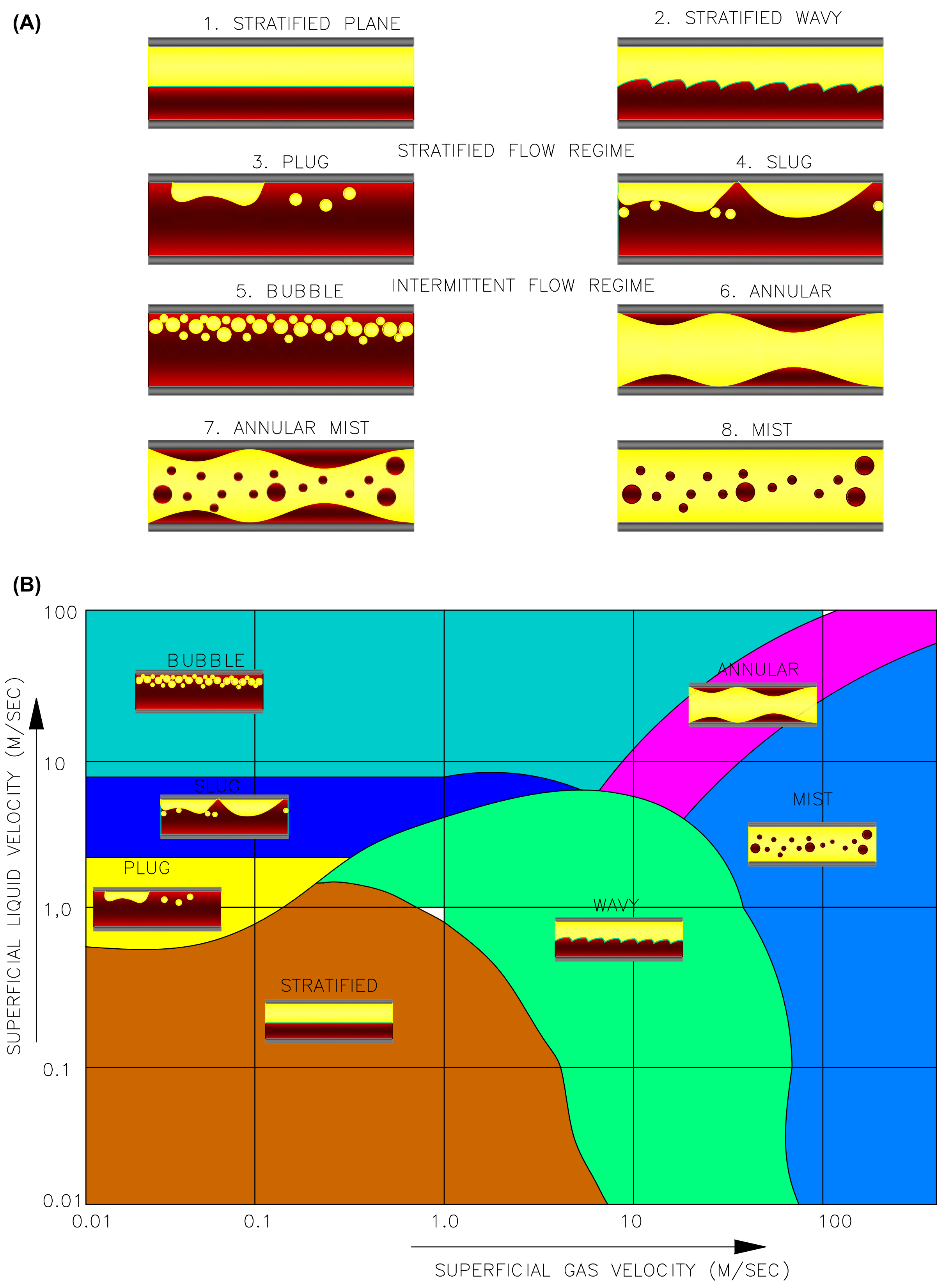


FIGURE IX/1.1.3-2 Horizontal pipe flow regimes and flow map. (A) Horizontal pipe flow regime. (B) Horizontal pipe flow map.

becomes annular, with a thicker film at the bottom of the channel owing to gravitational effects.

- *Annular mist:* This is basically annular flow but with liquid droplets at the center gas core.
- *Mist:* At very high velocity the intensity of turbulence is enough to disperse the bubble about the cross-section of the conduit to give rise to a mist flow.

6. **Flow maps:** Flow maps, often called flow regime maps, represent the graphical presentation of observations of flow patterns to the plot. Usually two superficial velocities, i.e., superficial velocities of liquid and gas phases, are used as axes for the graph. It is *customary* to represent superficial velocities of gas and liquids as the X axis and Y axis, respectively. However, graph axes can also represent the flow rates of the two phases or total mass flux on one axis and the mass fraction of the flow on the other. After completing all the observations, and recording the same, boundary lines are drawn on the graph. There are two types of flow maps as depicted in Fig. IX/1.1.3-1B and Fig. IX/1.1.3-2B for vertical and horizontal flows. It is important to note that such graphical representations are valid for specific multiphase fluid at specified pressure in a specified conduit only.
7. **Transition flooding and reversal:** The following are some important phenomena worth noting.
   - *Transition:* On account of the random motion of the bubbles within a conduit this may lead to bubble collisions, resulting in coalescence of bubbles. However, at higher turbulence (high velocity), the large bubbles may be broken down and, also, the residence time in the conduit may be insufficient for enough bubble coalescence to occur, hence giving rise to slug flow. On the other hand, at low void fractions the collision frequency may tend to be zero. Also, surface contaminants prevent coalescence of bubbles, formation of froths, or bubbles with contaminants. Bubble flow can exist up to very high void fractions >0.9 [5]. An important phenomenon transition has been discussed in Subsection 1.2.2.1.
   - *Flooding:* As the gas flow is increased, the system passes from one of a falling film flow through the transition at which liquid begins to travel upwards to simultaneous upward and downward flow, i.e., both climbing and falling film flow occur simultaneously. This transition (region) is referred to as "flooding." The onset of flooding is extremely sensitive to the entrance geometry. Also, it has been noted that flooding is caused by the formation of large waves on the interface.
   - *Flow reversal:* When the gas velocity is reduced, a point will be reached at which the liquid phase, in addition to flowing upwards, begins to creep down the tube wall from the injection point. This transition point is called the "flow reversal" point. The *flow reversal* transitions are relatively insensitive to the liquid flow rate, and can occur at an approximately constant gas superficial velocity [6].
8. **Slip and slip effect:** To start the discussions we recall the definition of gas/liquid volume fraction and gas void fraction and hold up area for liquid, as explained in Table IX/1.1.1-1. The velocity of gas is normally higher than that of liquid. With reference to Table IX/1.1.1-1, we get that a slip denotes the difference between the two velocities. So, when gas and liquid flow in a pipe, liquid will cover more of the cross-section than that under nonflowing conditions. This is due to the effect of slip between liquid and gas. As a result of this the lighter gas phase will normally move much faster than the liquid phase, and hence gas fraction will be less and the liquid has the tendency to accumulate in horizontal and inclined pipe segments. This is clearly shown in Fig. IX/1.1.3-3, where both slip and no slip have been elaborated. As shown in the figure, when there is no slip gas GVF and LVF are the same and both gas and liquid velocities are the same. When there is a slip for the same GVF the void fraction is much less than GVF.

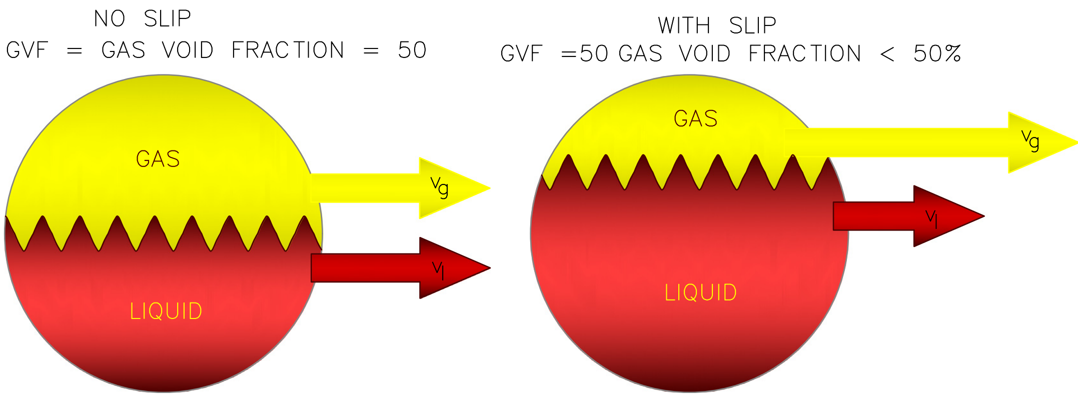


FIGURE IX/1.1.3-3 Slip and slip effect. When both gas and liquid are the same then GVF and gas void fraction are the same. When the velocity of gas is much higher than that of liquid then for the same GVF the gas void fraction will reduce as gas is quickly evacuated due to high velocity. For GVF, void fraction, and K refer to Fig. IX/1.1.1-1.

The liquid (α_l) or gas fraction (α_g) of the pipe cross-sectional area (A) as measured under two-phase flow conditions, is known as liquid hold-up (λ_l) and gas void fraction (λ_g) as elaborated in Table IX/1.1.1-1. Subscripts l and g represent liquid and gas, respectively. Therefore,

$$\lambda_l = A_l/A$$

and

$$\lambda_g = A_g/A \qquad \text{(IX/1.1.3-1)}$$

Referring to Table IX/1.1.1-1, we get

$$\alpha_l + \alpha_g = 1 \qquad \text{(IX/1.1.3-2)}$$

Also,

$$\lambda_g + \lambda_l = 1 \qquad \text{(IX/1.1.3-3)}$$

Thus, from Fig. IX/1.1.3-3, for situation with slip one would get,

$$\lambda_l \geq \alpha_l$$

but

$$\lambda_g \leq \alpha_g \qquad \text{(IX/1.1.3-4)}$$

Referring to Table IX/1.1.1-1 for definition of superficial phase velocity one gets,

$$v_{sg} = (q_g)/(A_{pipe}) = (q_g)/(A_g)\cdot(A_g)/(A_{pipe}) = v_g\cdot\lambda_g \qquad \text{(IX/1.1.3-5)}$$

similarly,

$$v_{sl} = (q_l)/(A_{pipe}) = (q_l)/(A_l)\cdot(A_l)/(A_{pipe}) = v_l\cdot\lambda_l \qquad \text{(IX/1.1.3-6)}$$

Thus, from Eqs. IX/1.1.3-5 and IX/1.1.3-6 one gets that the superficial velocity is related to the respective velocity in terms of void fraction/liquid hold up.

With this basic idea on multiphase flow, discussions on two-phase flow as a special case of multiphase flow metering will be discussed in the next section.

1.2.0 Two-Phase Flow Measurement

Multiphase flow measurements are complex, and major research works have been undertaken all over the world. The majority of these are in connection with the oil and gas industries. However, in industrial plants there are many plants and industrial application areas where there are requirements for multiphase flow, but in the majority of such cases the requirements are for two-phase measurement, i.e., the most common class of multiphase flows is two-phase flows. Two-phase flow measurement is a subdivision of multiphase flow measurement. This section is dedicated to two-phase flow measurements. Let the discussions start with some examples

and recapitulations. There are four classes of two-phase flow, as already indicated above:

- **Gas—liquid flow:** Steam water flow in thermal/nuclear power plants is an example of gas and liquid two-phase flow. In this case both phases have a chemical substance. Argon—water or air—water are examples of two-phase multicomponent flow.
- **Gas—solid flow:** A fluidized bed is an example of gas—solid flow. However, conveying of solids, such as cement, grains, metal powders, ores, and coal are only a few examples of pneumatic conveying involving two-phase flow and are mostly used in industry. For further details on solid conveying pneumatically, Chapter VIII may be referenced.
- **Liquid—solid flow:** Examples of this type of flow include flow of mud, various slurry flows (Chapter VII), flow of corpuscles in plasma, and the motion of liquid in aquifers. Discussions on slurry flow in Chapter VII may be referenced for further details.
- **Liquid—liquid flow:** The flow of two immiscible liquids, like oil and water in the oil recovery process, is an important application and is an example of liquid—liquid flow. Quite often in industrial processes, water is injected into the oil flowing in the pipeline to reduce the resistance to flow and the pressure gradient. In liquid extraction processes, solutes dissolved in a liquid solution are separated by another immiscible liquid. The polymer processing industry also requires two-phase/component flow measurement.

We now look into some basic mechanical details necessary to understand two-phase flow.

1.2.1 UNDERSTANDING TWO-PHASE FLOW

The basic purpose of this section is to clarify a few terms normally encountered in two-phase flow for basic understanding. Basic terms used in two-phase flow, such as mass flux, dryness fraction, GVF, slip, slip ratio, etc. have already been defined and covered in Table IX/1.1.1-1 and in previous section, hence these are not repeated here.

1. **Two-phase and phase change phenomenon:** In general two-flow phenomena should be considered adiabatic and the phases have different chemical compositions (oil & water), or single-component two-phase flows, for example, the flow of steam and water in a boiler/condenser in a power plant. In some cases, there will be two-phase flow with different phases on account of change of phase (generally due to heat transfer). Obviously, *phase change* phenomena can be solid—liquid and gas (vapor)—liquid phase change phenomena.
   - *Melting solidification:* The first category includes the process of melting and solidification. In both the cases, one of the phases is a solid and the other phase is liquid and can have a velocity field mainly due to natural convection. Heat transfer is often considered a static heat transfer issue.
   - *Boiling and condensation:* The second category of phase changes includes the processes —boiling and condensation involving vapor—liquid phase change. On account of the large density difference between two fluids, i.e., liquid and vapor, the movement cannot be overlooked. There are many challenging and variable issues involved, especially for nucleate boiling and departure from it, as in supercritical boilers. Details on these are available in the author's book [7]. In the majority of industrial and process plants the process involves boiling/condensation. Some of these plants are listed here:
     - Steam power cycle in both fossil fuel and nuclear power plants;
     - Refrigeration and air conditioning;
     - Cryogenics;
     - Oil and gas plants;
     - Chemical industries;

- ○ Material beneficiation plants;
- ○ Electronic cooling;
- ○ Biochemical and food engineering.

Though both boiling and condensation involve vapor–liquid phase change they have some gross differences also.

2. **Pressure drop:** The pressure drop is a very important parameter in any flow-measuring systems, but more so in two-phase with adiabatic systems and for systems involving phase change, i.e., boilers and condensers. In two-phase flow systems pressure drops can occur on account of gravity, friction, and acceleration. Therefore, with pressure drop in conjunction with the flow there will be energy loss in the system. In two-phase flow the same concept of *all-liquid* frictional pressure drop (as is done in single-phase flow) is useful to tie into single-phase results at one end and eliminates any ambiguity about the physical properties to use, especially viscosity. Also, the all-liquid frictional pressure drop is chosen over all-gas frictional pressure drop, because the liquid density generally does not vary in a problem, while the gas density changes with pressure. Therefore, for a system requiring fixed flow, the pressure drop becomes a key factor in determining the power requirement for the system. If the available pressure drop is fixed, then the relationship between velocity and pressure drop determines the flow rate. In forced circulation the pressure drop governs the pumping power requirement. On the other hand, in natural circulation systems, pressure drop is the key parameter to determine the rate of circulation, and as a consequence other parameters are arrived at. Also, the importance of pressure drop lies with the formation of different types of two-phase flow patterns in the conduit due to two-phase flow. Such patterns are important in tackling design and operational problems. Accurate prediction of pressure drop is extremely important for horizontal and vertical, as well as inclined, pipelines for two-phase flow systems (e.g., directional wells).
3. **Mass transfer and mass transfer coefficient:** This physical phenomenon, along with the heat transfer phenomenon, is extremely important for the study of two-phase flow.
   - *Mass transfer:* As indicated in the initial discussions, mass transfer basically means the changes in transition to a turbulent flow. It involves the transport of a substance (mass) between two phases, i.e., liquid and gaseous media. Depending on the conditions, the nature, and the forces responsible for mass transfer, four basic types are distinguished [8]:
     - ○ Diffusion in a quiescent medium;
     - ○ Mass transfer in laminar flow;
     - ○ Mass transfer in turbulent flow;
     - ○ Mass exchange between phases.
   - *Mass transfer coefficient:* Chemical potential driving force, expressed in terms of concentration (partial pressure), is responsible for mass transfer across an interface, or virtual surface in the bulk of a phase. The rate of transfer of a given substance per unit area normal to the surface can be considered as mass transfer. Mass transfer is dependent on some of the physical properties of the system and on the degree of turbulence. It is not easy to establish the relationship between mass transfer and these parameters. Therefore, the mass transfer coefficient is established through complex mathematical equations (a standard mechanical or mass heat transfer book may be referenced). The mass transfer coefficient is important not only for separation of equipment design but also in predicting the situation of combined heat and mass transfer such as in the condensation of vapor mixtures.
4. **Heat transfer coefficient:** Mass transfer mostly occurs in combination with heat transfer and is very important for industrial system design and understanding. This is important in two-phase flow, especially involving phase change such as a thermo siphon reboiler distillation plant or a condenser in a thermal power plant.

Heat transfer coefficients in two-phase systems are used for determining the size of heat exchangers in such systems.

5. **Mean phase content:** This basically stands for void fraction for gas and hold up area for liquid, as already explained.

We now look into some details about various types of two-phase flow and their properties with special reference to industrial applications.

1.2.2 TYPES OF TWO-PHASE FLOW PHENOMENA

Previously in Section 1.1.3 of this chapter we had seen various characteristic flow regimes in vertical and horizontal conduit. In this section various phenomenon involved for these flow regimes and their transitions shall be discussed. are discussed to complete the study of two-phase flows normally encountered in various processes and industrial plants. The discussion starts with gas–liquid two-phase flow.

1. **Gas–liquid:** As described in Subsection 1.1.3.7, it can be seen that in two-phase flow of gas and liquid there will be various flow patterns both in vertical as well as horizontal conduits. It is important to note why and how such flow patterns change. The major transitions are discussed here.
   - *Vertical conduit bubble–plug transition:* The transition from bubble to plug patterns occurs due to *bubble coalescence* for which there will be bubble growth and finally the formation of large Taylor-type bubbles to occupy the whole pipe cross-section. Typically, at a void fraction of 25%–30% this happens (slug). At high turbulent flows they break up and plug flow occurs to offset the progression of the coalescence. It is possible that void waves formed in the flow and within these waves, the bubbles become closely packed and are better able to coalesce, leading to plug flow (Beisheuvel and Gorissen, 1990).
   - *Vertical conduit plug–annular flow transition:* This regime is entered from slug flow by the formation of flooding-type waves and these persist as a characteristic of the regime throughout. These waves, discussed above, are absent in both slug flow and annular flow, but are formed repeatedly in the churn flow regime and transport the liquid upwards. The onset of churn flow is accompanied by a sharp increase in the pressure gradient. In between successive flooding waves the flow of the liquid phase in the film region near the wall reverses direction, and is eventually entrained by the next upward-moving wave.
   - *Vertical conduit churn–annular flow transition:* When the gas velocity is increased after the churn flow regime, the pressure gradient initially decreases and crosses the minimum value. The flooding waves and associated intensive gas–liquid interactions cause an increase in pressure gradients, and, as they disappear, the pressure gradient reduces. With a further increase in flow rate, the pressure gradient increases. The onset of annular flow occurs at a point at which there is no flow reversal within the liquid film. This might correspond approximately to the pressure drop minimum (maybe not accurately so) [9]. Another definition might be the flow reversal point, as defined earlier.
   - *Horizontal conduit stratified–slug transition:* The Taitel and Ducker (1976) model ascribed this transition to the onset of Kelvin–Helmholz instability and applied an inviscid form of this instability to the prediction of the transition [9]. However, later some correction factors were introduced and viscosity was taken into account for better prediction. In any case there still exists some uncertainty in the prediction of this transition.
   - *Horizontal conduit slug–annular transition:* Here also Kelvin–Helmholz instability was applied and it was assumed that this would occur when the equilibrium liquid level at the onset of less than half the conduit diameter. However, this explanation does not always fit well for the transition.
   - *Horizontal conduit slug–dispersed bubble transition:* This is often conceived as the

capability of the turbulence in the liquid phase to suspend the bubbles. When the bubbles cannot be suspended, then they group to form the gas bubble regions in slug flow. Frankly speaking, real explanations are too complex and this calls for further investigation.

2. **Gas–solid:** As described earlier pneumatic conveying of solids and fluidized beds are major application areas in this type of two-phase flow. Apart from these, two-phase flow applications are also found in particulate pollution control, food products drying, and plasma-arc coating. Therefore, it is important to investigate various issues. Pneumatic conveyed flow meter types have been discussed in Chapter VIII. Major issues are listed here:
   - *Pneumatic transport:* Pneumatic transport is very important from the application point of view, i.e., transportation of metal particles, grains, ores, cement, pulverized coal, and other powdery products which do not get damaged due to contact with the pipe walls. Advantages including the flexibility of line location and the capability to tap the line at arbitrary locations make them versatile in use. The only restriction is that the gas velocity for vertical transport must exceed the settling velocity of the particles to make effective flow. Depending on major factors like particle-loading flow velocity, there are various flow patterns found in horizontal pneumatic transport, as shown in Fig. IX/1.2.2-1.

     With a decrease in velocity flow patterns change from *homogeneous* flow to *packed bed* flow patterns in stages like dune flows and slug flows. Change from homogeneous

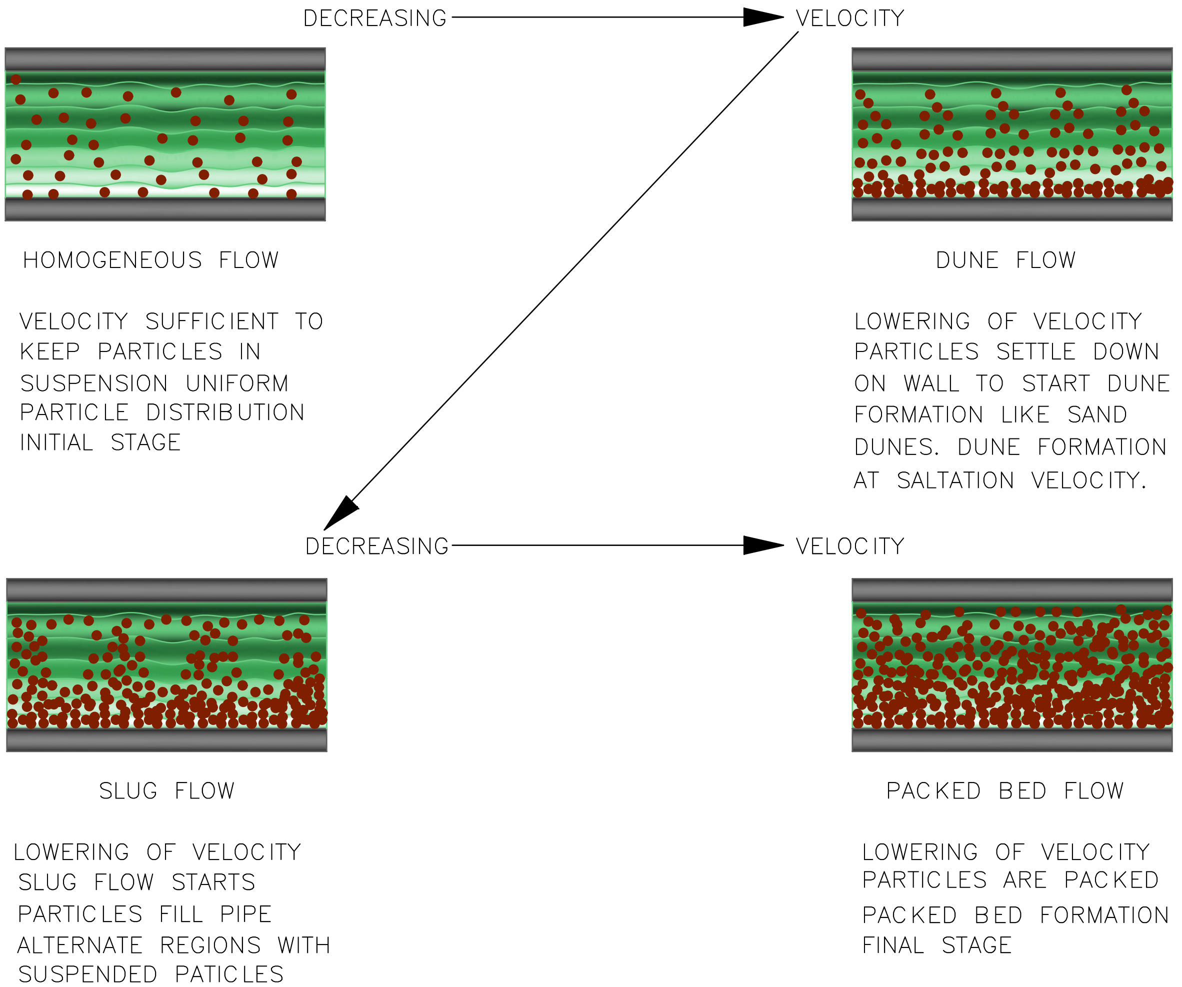


FIGURE IX/1.2.2-1 Horizontal pneumatic conveying flow types.

flow to dune flow occurs at a velocity referred to as *saltation* velocity. Transformation of each stage has been elaborated in Fig. IX/1.2.2-1.

- *Fluidized bed:* In a fluidized bed, the container is loaded with particles of interest and it is supplied with a gas through a distributor plate in the bottom of the container to keep the particles in suspension. The fluidized bed is another good example of two-phase flow of gas and solids used in a type of boiler and combustion type, some chemical processes, such as coal gasification and liquefaction roasting ores, and waste disposal.
- *Pollution control:* Cyclone separators and electrostatic precipitators are examples of pollution control devices. Details on the functioning of electrostatic precipitators are available in Ref. [7]. These cyclone separators are not only used for pollution control but are also used in cement plants as production control equipment.

3. **Liquid−solid:** Liquid−solid flow represents the flow of a liquid continuum carrying solid particles conveyed by the drag and pressure forces of the liquid acting on them. These represent mainly slurry flow, as discussed at length in Chapter VII. Liquid−solid flows are of two types: total mixture flow characterized by the pipe Reynolds number (Re) and the low flow between the solid particles and the carrier fluid characterized by the particle Reynolds number (Re) (refer to Section 2.1.2 of Chapter VII). Unlike pure liquids, a full range of velocities is not possible with slurries. Two phases influence each other so it is necessary to ensure that they are harmonized properly, to make effective flow without depositions or blockages. Rheological behavior of matter and change of the same from a Newtonian to a non-Newtonian one, flow behavior, flow regime, and the influence of rheology on slurry flow have been discussed at length in Chapter VII and are not repeated here. For larger particles, on account of the force of inertia, they remain separated and not much changed in viscosity. Also, for any concentration, the flow behavior is guided by the behavior of the carrier fluid for large particles and for fine particles <20%−25% concentration but beyond that for fine particles slurry flow behavior changes. A relatively low tendency towards *segregation* exists for vertical flow as a result of the symmetrical configuration of forces even for coarse materials. For further details and flow behavior, etc. discussions in Chapter VII may be referenced.
4. **Liquid−liquid:** Wide varieties of flow patterns are found when two immiscible fluids are present in a conduit. These may be stratified or mixing types based on velocity. At lower velocity they may be in a stratified form and at high velocity they can be the dispersed type. Based on *hydrodynamics* liquid−liquid two-phase flow can be categorized as:
   - *Separated flows:* This type of flow occurs at low-velocity laminar flow. The parallel flows of two immiscible fluids could be found in channel. With an increase in the flow rates of the phases, waves start appearing at the interface.
   - *Dispersed flows:* With increased turbulence breakage of one phase into the other takes place, as shown in Fig. IX/1.2.2-2. The variations have been indicated in Fig. IX/1.2.2-2. With dispersions, the dependence on viscosity increases.
   - *Phase inversion:* In liquid−liquid systems, phase inversion is a type of flow. It is important to know the conditions governing phase inversion. Phase inversion is defined as the point at which the continuous phase becomes the dispersed one and vice versa, also at this point the viscosity of the mixture reaches a peak. Thus, an inversion point represents a change from an oil-in-water to a water-in-oil dispersion.

Discussions on the types of two-phase flow are complete and we now look into the details about void fraction issues and their significance in two-phase flow.

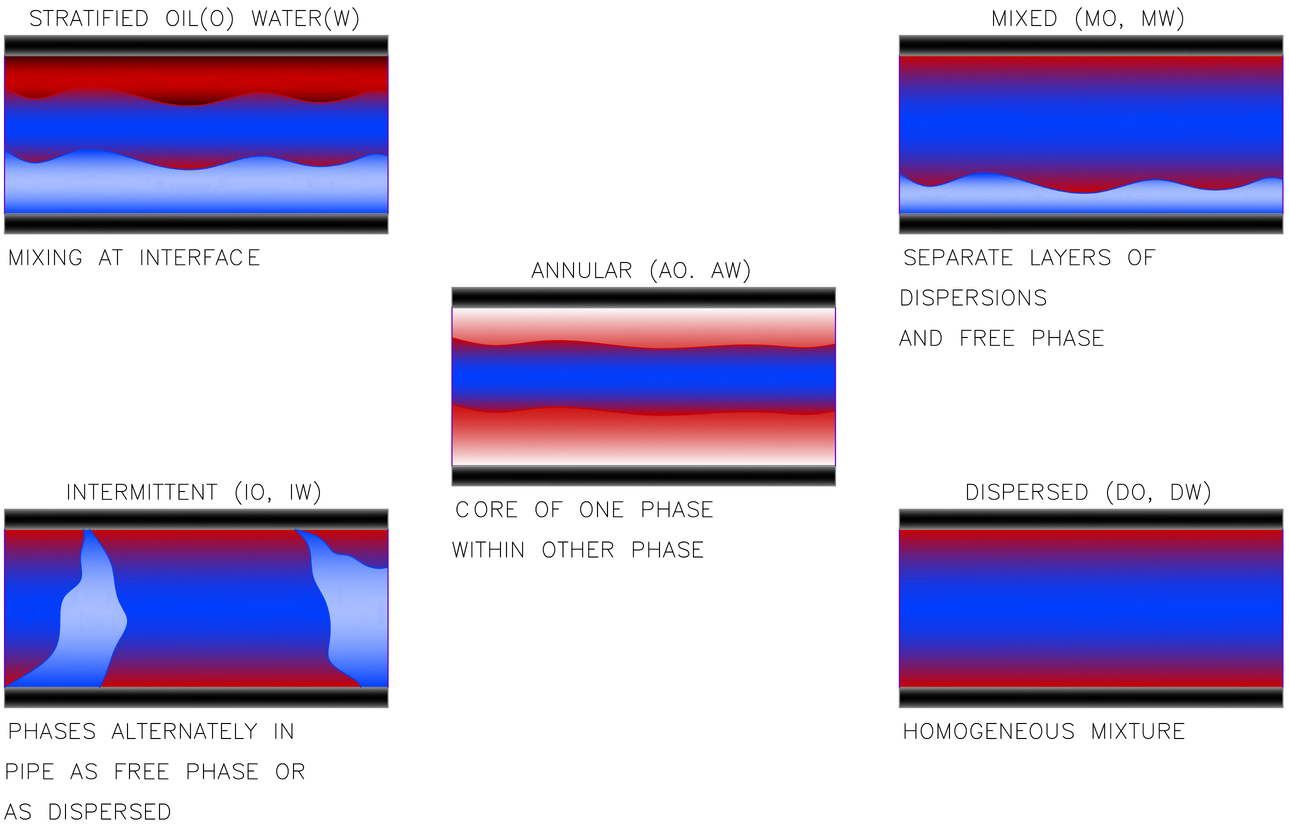


FIGURE IX/1.2.2-2 Immiscible liquid dispersed flow types.

1.2.3 VOID FRACTION AND VOID FRACTION MEASUREMENT IN TWO-PHASE FLOW

Two-phase multiphase flows are largely fluctuating and measurements call for the use of specific instrumentation. There have been many techniques for void fraction measurement but their success depends on the specific application. The signal response is two-phase flow structure-dependent and can be designed to indicate void fraction values that are instantaneous or time-averaged, local, or global. In this section discussions will be presented on phase/void fraction encountered in two-phase flow and how it influences the fluid mechanics for two-phase flow. Void fraction, defined in Table IX/1.1.1-1 and Fig. IX/1.1.1-1, plays an important role in characterization of the multiphase flow. Prediction of the performance of a system with two or more phases relies on correct measurements of the void fraction. There are several ways and means for measurement of the void fraction. In this section brief discussions on such measurement principles are covered. Also, brief mathematical derivation of a few popular methods for void fraction shall also be elaborated. Prior to starting such discussions it is important to define and explain a few terms relevant in phase/void fraction measurements. We start the discussion with a few frequently used terms and the geometrical significance of these terms.

1. **Relevant terms and geometrical significance:** In Table IX/1.1.1-1 and Fig. IX/1.1.1-1 an attempt has been made to define void

fraction. Void fraction and vapor quality are often confused. There is a geometrical significance to void fraction, which has been depicted in Fig. IX/1.2.3-1.

This will be helpful in understanding of void fraction measurement by various methods.

- *Void fraction and vapor quality in thermodynamics:* Generally, void fraction, unless stated otherwise, is defined as the local area ratio of area of gas and total area. On the other hand, vapor quality is represented by the ratio of mass of gas/vapor and total mass. Referring to 1 of Fig. IX/1.2.3-1, it can be seen that both gas and liquid are 50% in area, so the void fraction is ½. If the density of gas and liquid are represented by ρ_g and ρ_l such that $\rho_l = 5^* \rho_g$ and if area of conduit is A. Then the mass of gas $= 0.5A^* \ \rho_g$; mass of liquid $= 0.5A^* \rho_l = 0.5A^* 5^* \rho_g$.

  Vapor quality (x) = mass of gas/total mass, i.e., $(0.5A^* \ \rho_g)/(0.5A^* \ \rho_g + 0.5A^* 5^* \rho_g) = 1/6$. For vapor quality (ratio), length parameter is not significant hence not shown for mass computation.
- *Local (point) void fraction:* This is defined in terms of the point method, as shown in 2 of Fig. IX/1.2.3-1.

  Based on the distribution of point at any time (t), function can be defined for any

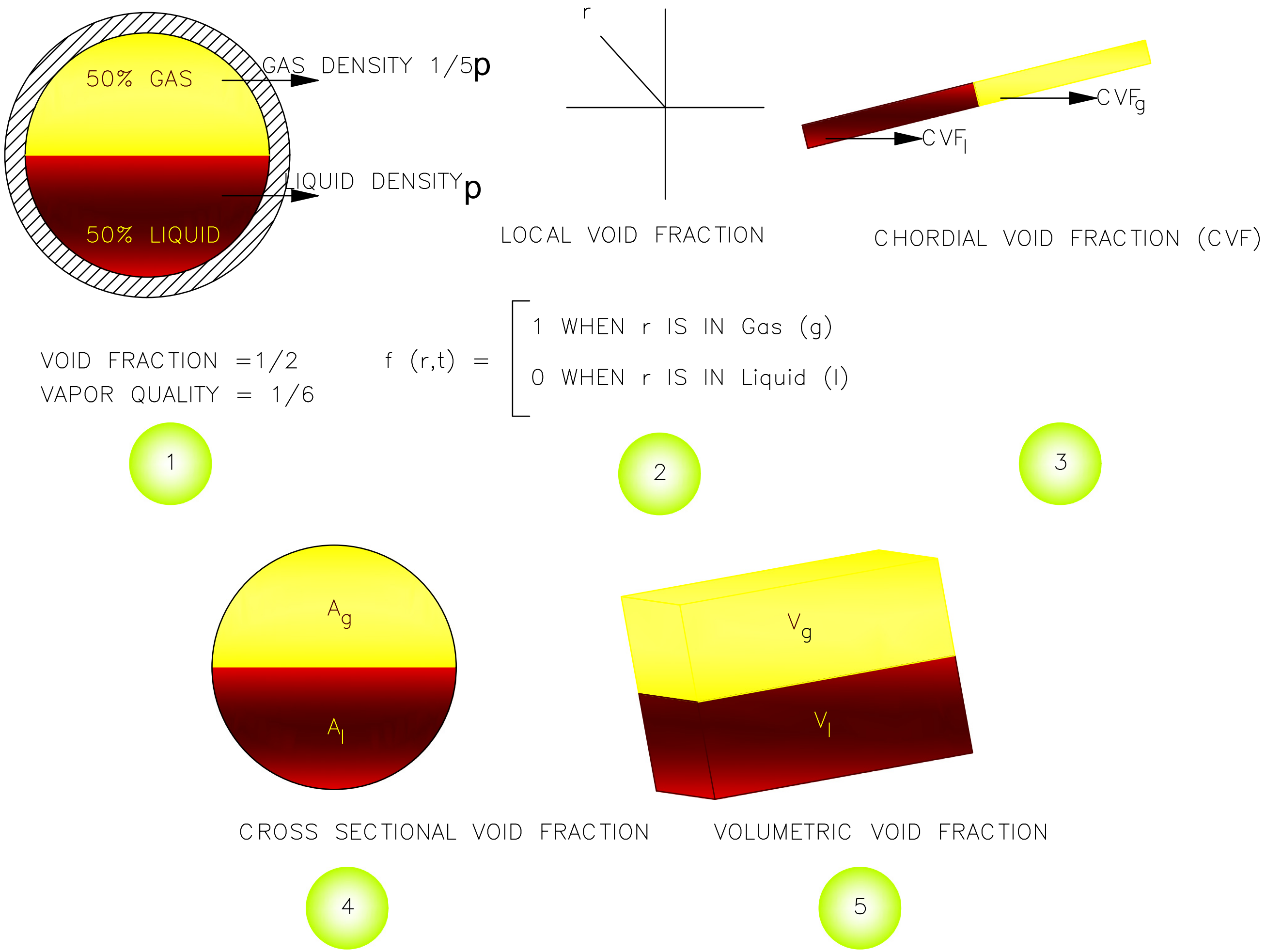


FIGURE IX/1.2.3-1 Void fraction geometrical significance.

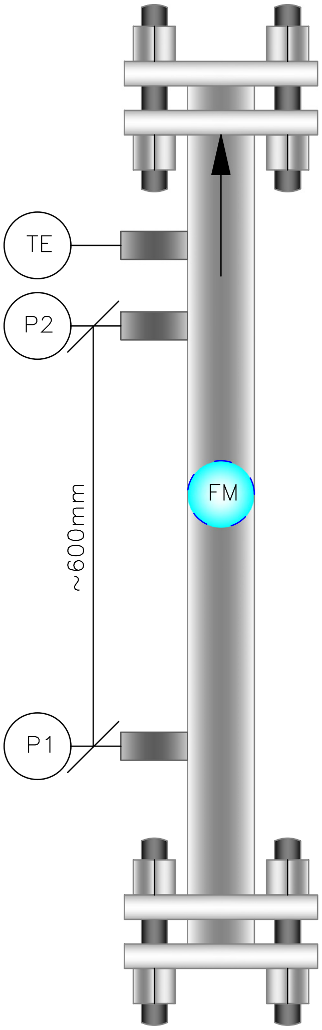


FIGURE IX/1.2.3-2 DP measurement for void fraction. *FM* = In-line flow meter velocity measurement (as necessary) temperature sensor for viscosity correction. *P1* = pressure tapping for absolute pressure transmitter 1; *P2* = pressure tapping for absolute pressure transmitter 2; *TE* = temperature element for temperature sensor.

point r as: f (r, t) = 1 if point r is in a gas phase; and 0 if point r is in liquid:

Void fraction

$$\varepsilon_{local} = \lim_{t-\infty} \frac{1}{t} \int_0^t f(r,t)dt \qquad \text{(IX/1.2.3-1)}$$

- *Chordal void fraction:* With reference to 3 of Fig. IX/1.2.3-1, one gets

$$\varepsilon_{chordal} = \frac{L_g}{(L_g + L_l)} \qquad \text{(IX/1.2.3-2)}$$

- *Area (cross-sectional) void fraction*: With reference to 4 of Fig. IX/1.2.3-1 one finds that

$$\lambda_g/\varepsilon_{(area/cross\ section)} = \frac{A_g}{(A_g + A_l)} \qquad \text{(IX/1.2.3-3)}$$

- *Volumetric void fraction:* With reference to 5 of Fig. IX/1.2.3-1, one gets

$$\varepsilon_{vol} = \frac{V_g}{(V_g + V_l)} \qquad \text{(IX/1.2.3-4)}$$

or

$$\varepsilon_{vol} = \frac{q_g}{(q_g + q_l)} \text{ or } \frac{q_g}{(q)} \qquad \text{(IX/1.2.3-5)}$$

where "q" represents the corresponding volume flow rate.

- *Liquid and gas (vapor) velocity:* Velocities of gas (v_g) and liquid (v_l) have already been described, now they are defined with vapor quality as follows:

$$v_g = (q_g)/(A\cdot\varepsilon) = (q_{mg})/(\rho_g)\cdot(x)/(1-\varepsilon) \qquad \text{(IX/1.2.3-6)}$$

$$v_l = (q_l)/(A)\cdot(1-\varepsilon) = (q_{ml})/(\rho_l)\cdot(1-x)/(1-\varepsilon) \qquad \text{(IX/1.2.3-7)}$$

Here x stands to represent vapor quality described above. In homogeneous flow, $v_g = v_l$.

Each of the above methods of phase/void fraction definition is related to a set of measurement type. In the following subsections

these will be described individually. Brief discussions of these types will be given, starting with differential pressure type based on energy balance (*hence on mass—actually volumetric type because densities are converted using volumetric void fraction*).

2. **Differential pressure measurement (volumetric void fraction):** Based on Bernoulli's equation of energy conservation, the correlation of differential pressure and void fraction can be arrived at. From Chapter I, we know that Bernoulli's energy equation states:

$$1/2\ \rho v^2 + \rho g h + P = \text{constant} \quad \text{(IX/1.2.3-8)}$$

In this derivation all symbols have a standard meaning (as indicated in Chapter I). Here $\frac{1}{2}\rho v^2$ is kinetic energy, ρgh is potential energy, and P is pressure. So, with two tapping points where the pressure sensors could be located we get

$$1/2\ \rho_m v_1^2 + \rho_m g\, h_1 + P_1 = 1/2\ \rho_m v_2^2 + \rho_m g\, h_2 + P_2 + F_p \quad \text{(IX/1.2.3-9)}$$

where ρ_m is the gas–liquid mixture density, and F_p is the frictional pressure loss. Since the pipe is of uniform cross-sectional area without any restriction (as used in head type measurement) it will not be far wrong to assume $v_1 = v_2 = v$, therefore, the kinetic energy on both sides can be *cancelled*.

$$\rho_m g h_1 + P_1 = \rho_m g h_2 + P_2 + F_p \quad \text{(IX/1.2.3-10)}$$

As shown in Fig. IX/1.2.3-1, the tapping point of the first sensor as a reference point, i.e., $h_1 = 0$ and the height of other sensor $h_2 = h$. Eq. IX/1.2.3-10 is simplified to

$$P_1 = \rho_m g h + P_2 + F_p \quad \text{(IX/1.2.3-11)}$$

or

$$\Delta P = P_1 - P_2 = \rho_m g h + F_p \quad \text{(IX/1.2.3-12)}$$

Since for mass flow rate $q_m = q_{mg} + q_{ml}$, hence $q^*\ \rho_m = qg^*\ \rho_g + q_l^*\ \rho_l$.

Now using Eq. IX/1.2.3-5, and replacing q_g & q_l, one gets $\rho_m = \varepsilon\rho_g + (1-\varepsilon)\rho_l$ where ρ_m, ρ_g, and ρ_l are densities of mixture, gas, and liquid, respectively, so substituting the value in Eq. IX/1.2.3-12 above one gets,

$$\varepsilon = \frac{\Delta P - \rho_l \cdot g \cdot h - F_p}{(\rho_g - \rho_l) g \cdot h} \quad \text{(IX/1.2.3-13)}$$

Frictional pressure

$$\text{loss } F_p = \left(2C_f \cdot \rho_m \cdot h\, v_1^2\right)/D \quad \text{(IX/1.2.3-14)}$$

For derivation of frictional loss, F_p, any standard book on fluid mechanics can be referenced.

In order to get F_p one has to predetermine fanning factor and the liquid velocity. C_f is formulated into different formats in terms of the different flow conditions and the roughness of the pipe. It is related to Reynolds number (R_e) as

$$C_f = 0.079 \times R_e^{-0.25} \quad \text{(IX/1.2.3-15)}$$

The determination of viscosity and liquid velocity are challenging. In many cases temperature sensors are used to take care of base viscosity change and a velocity type flow sensor for determining liquid velocity (e.g., electromagnetic flow meter in series can be used provided there is conductivity in the flowing fluid. Axial turbine meters are also seen).

3. **Electrical impedance technology (volumetric void fraction):** The electrical impedance techniques have been developed based on the difference in conductivity and/or relative permittivity of the liquid and gas phases in a two-phase fluid mixture. These impedance probes are low-cost and easily constructible instruments. They offer a high-frequency response and easy installation. The electrodes

are placed at the perimeter of a pipe for measuring impedance across the electrodes. From such measurements, it is possible to deduce the void fraction of the mixture/two-phase fluid. For void fraction measurement, there are many different possibilities to arrange the set of electrodes across (on the perimeter of) the conduit. There are two kinds of electrical impedance techniques: electrical conductivity and capacitance probes. Depending on the type of instrumentation used and the liquid material to be investigated, either of these two can be implemented for the majority (almost all) of measurement types. The electrical impedance technique has a variety of advantages, such as easy implementation, no intrusiveness of flow field, no radiation, and convenient mobility. On account of this electrical-impedance technique, it has received much attention and various designs have been developed. Electrical impedance type measurements are non intrusive and some are noninvasive also, such as the capacitance impedance probe.

- *Conductivity type:* Normally, conductivity probes are flush-mounted ring electrodes mounted in the perimeter of the conduit to measure the conductivity of two-phase fluid. A typical arrangement is represented by two metallic rings annealed in the pipe inner wall to measure the conductivity of two-phase fluids. There are two types of electrode configurations, i.e., full ring and half ring conductivity electrodes, as shown in Fig. IX/1.2.3-3A. For conductivity measurement, a controlled electrical current is injected into the flow, and then the voltage drop between two electrodes along an insulated section of the pipe is measured. Therefore, from the measured voltage drop for a known injected current, the resistance (or conductance) is calculated by Ohm's law, and hence the conductivity can be calculated from the given geometry. Here the electrode can be both contact and noncontact types.
- *Capacitance type*: When the conductivity of the two-phase substances are low i.e., oil, capacitance probes can be used as impedance probes. Permittivity—an electrical property will be different for each of the three components, i.e., gas/oil/water in the mixture. Accordingly, the permittivity of the mixture is a measure of the fractions of the different components. This type of measuring system applied for two (or three)-phase flow measurement is a fully noninvasive way to measure void fractions. Capacitance (C) between two plates is given by $C = \frac{\varepsilon_0 \cdot A}{d}$, where ε_0 is permittivity (also called dielectric constant) in a vacuum, A is the area of the plate, and d is the distance between two plates. In a generalized way void fractions for three elements, such as gas (ε_g), oil (ε_o) and water (ε_w). are given by the generalized equation:

$$
\begin{aligned}
A\varepsilon_g + B\varepsilon_o + B\varepsilon_w &= V_1; C\varepsilon_g + D\varepsilon_o + F\varepsilon_w \\
&= V_2; \&\ \varepsilon_g + \varepsilon_o + \varepsilon_w \\
&= 1.
\end{aligned}
$$

where A, B, C, D, E, and F are constants and depend on fluid properties and sensor geometry. Here *two issues* to be noted are that for three unknown variables ε_g, ε_o, and ε_w three equations are necessary, as indicated. Therefore, for three-phase fractions a second set of measurements with a capacitance probe will be necessary. The electrodes will act as a capacitance detector and the resulting capacitance can be measured between the electrodes. This capacitance measurement works as long as the oil flow is continuous, i.e., water is

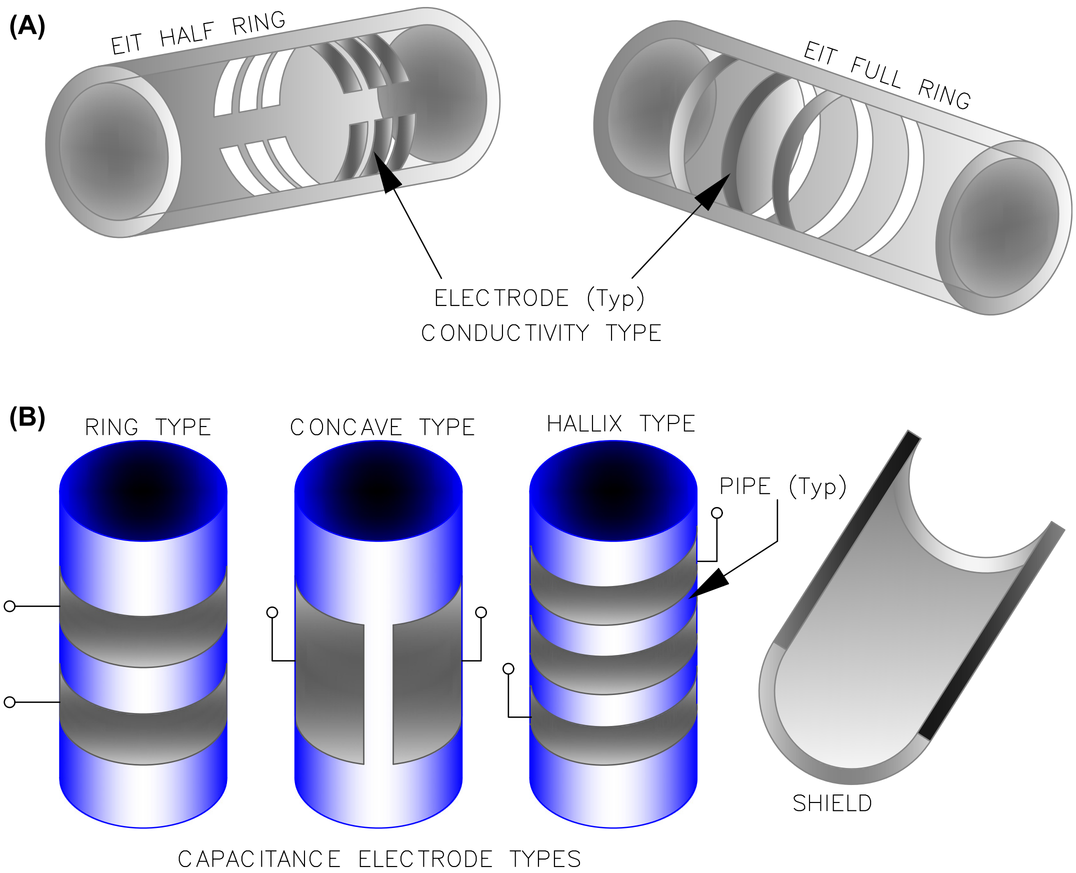


FIGURE IX/1.2.3-3 Area void fraction by EIT sensing. (A) EIT sensor conductivity type. (B) EIT sensor capacitance type.

dispersed in the oil (no continuous path i.e., with water cut <65%). There are a number of sensor types, such as ring type sensor, concave type sensor, and helical type sensor (along with shield), as shown in Fig. IX/1.2.3-3B. Normally, capacitance is in the range of 0.1−10 pF. Good signal to noise ratio is extremely important for correct void fraction measurement, hence proper shielding is essential.

4. **Gamma ray detection (area and chordal void fraction):** The cross-sectional averaged void fraction $\alpha_{c\text{-}s}$ yields from Eq. IX/1.2.3-3 as: $\varepsilon_{(area/CS)} = \frac{A_g}{(A_g+A_l)}$ at a given time. Whereas chordal void fraction $\varepsilon_{chordal} = \frac{L_g}{(L_g+L_l)}$ as given in Eq. IX/1.2.3-2.

Here it is important to note that a gamma ray can be deployed to measure both chordal void fraction as well as area void fraction.

A beam of gamma rays is attenuated by absorption and scattering according to the exponential absorption equation as follows:

$$I = I_0 e^{-\mu z} \qquad \text{(IX/1.2.3-16)}$$

where I is the intensity detected, I_0 is the incident intensity, μ is the linear absorption coefficient, and z is the distance traveled through the absorbing medium.

- *Area void fraction:* As is clear from the structure of the equation it is suitable for a single beam for an average path.

  A shield will be applicable for all cases for safety against hazards from the radioactive source. There are a number of detectors, such as gas tube, scintillating, and solid state detectors. In the majority cases scintillating counters are used. When the pulse count is in seconds, the error is injected into the system.

The standard deviation σ_R for count rate R and counting time τ is given by

$$\sigma_R = \sqrt{\frac{R}{\tau}} \quad \text{(IX/1.2.3-17)}$$

Often, counting time τ and source sizes are compromised for better rate R.

In order to measure area void fraction, normally, the intensities I_l and I_g are determined when the beam passes through the channel full of the liquid and gas phases, respectively. The void fraction is then usually related to the intensity in flowing condition, given by

$$\varepsilon_g = \frac{\ln I - \ln I_l}{\ln I_g - \ln I_l} \quad \text{(IX/1.2.3-18)}$$

For area void fraction measurement both single beams (or a single beam) as well as multibeam gamma rays, as shown in Fig. IX/1.2.3-4A and B, can be deployed.

Some other problematic issues come from the flow pattern of two-phase flow in a conduit. Another major source of error is associated with flow patterns in the channel. Eq. IX/1.2.3-18 only applies if the phases are homogeneously mixed, or if they exist in successive layers perpendicular to the beam [10]. If the liquid and vapor exist in layers parallel to the beam, then the void fraction is given by:

$$\varepsilon_g = \frac{I - I_l}{I_g - I_l} \quad \text{(IX/1.2.3-19)}$$

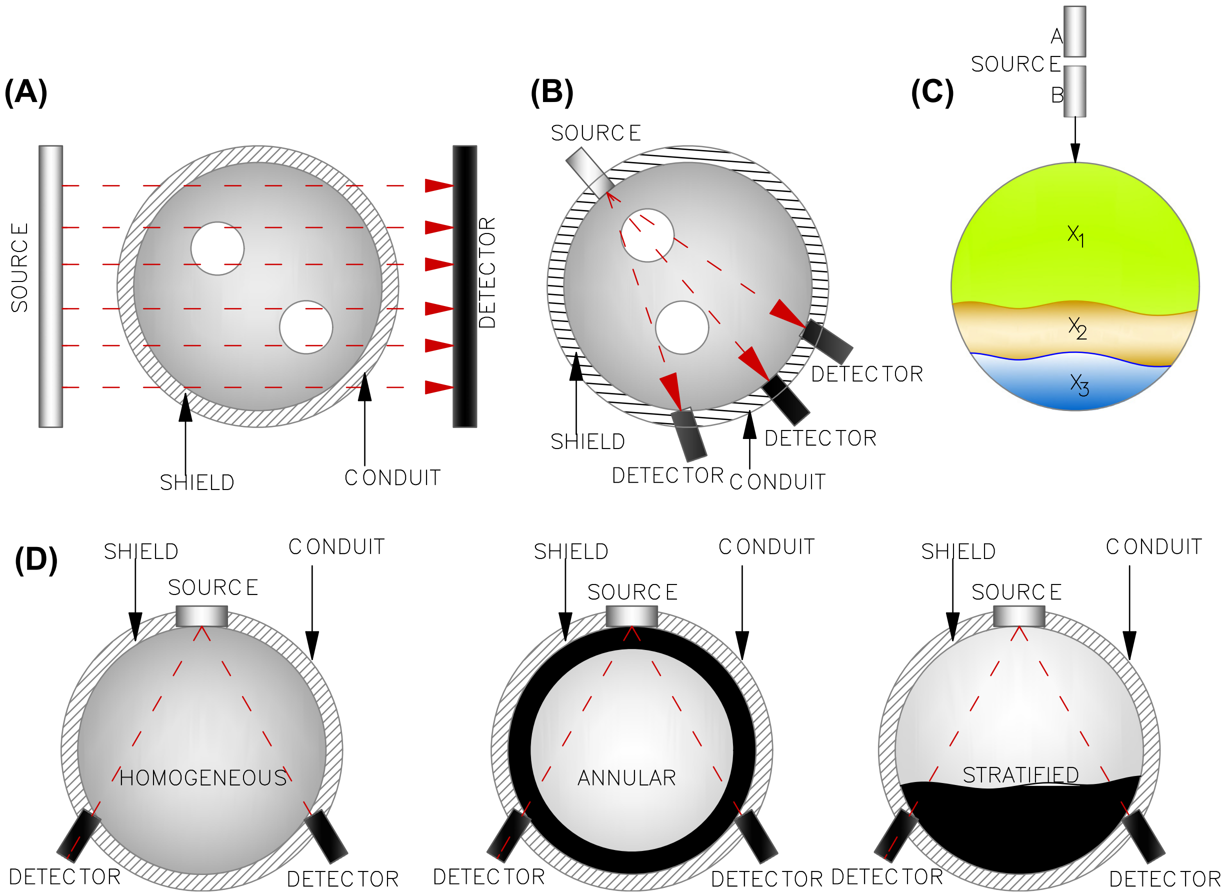


FIGURE IX/1.2.3-4 Gamma ray for void fraction (VF). (A) One shot. Source and detector shown apart for understanding only; all are within the shield. (B) Multibeam. (C) Chordal VF scheme. (D) Gamma detector for flow regimes.

Typical flow patterns, such as homogeneous flow, annular flow, and stratified flow are shown in Fig. IX/1.2.3-4D. Slug flow is a difficult flow pattern. In this flow pattern, the void fraction fluctuates on a time-average basis. This fundamental problem can be to some extent overcome by applying Eq. IX/1.2.3-18 *over short time intervals, and then calculating an average void fraction from the succession of values generated. The intervals should clearly be short compared to the fluctuation frequency within the system* [10].

- *Chordal void fraction:* Let us consider a situation as shown in Fig. IX/1.2.3-4C for chordal void fraction measurement.

  In the case of chordal measurement, Eq. IX/1.2.3-16 can be modified as:

$$I = I_0 \cdot e^{-(\mu_1 x_1 + \mu_2 x_2)} \quad \text{(IX/1.2.3-20)}$$

And

$$x_1 + x_2 = H(\text{total chord}) \quad \text{(IX/1.2.3-21)}$$

From the two equations it can be established that

$$\varepsilon_1 = \frac{L + \mu_2 H}{H \cdot (\mu_2 - \mu_1)} \left[\text{where } L = \ln \frac{I}{I_0}\right] \quad \text{(IX/1.2.3-22)}$$

The above equations can be generalized for three phases: x_1, x_2, and x_3. From the above only two sets of equation will be generated. On the other hand, there are three unknown variables, therefore, there should be dual sources to generate another equation. If the sources are A and B, for each of A and B there will be two sets of equations, like Eq. IX/1.2.3-20. Such a dual source is known as DEGRA, as detailed in Subsection 2.1.2.2. Thus these equations, in conjunction with Eq. IX/1.2.3-21 (modified as; $x_1 + x_2 + x_3 = H$), will constitute three sets of equations to find three unknown variables: ε_1, ε_2, and ε_3. Further details are also available in Section 3.3.1 also.

5. **Needle probe (local void fraction):** From Eq. IX/1.2.3-1 we get the local time-averaged void fraction. If we wait for a sufficiently long time, one would get the relation between the cumulated residence time of the gas T_g and the cumulated residence time of the liquid phases T_l within the time interval T as

$$\varepsilon_{local} = \frac{T_g}{T_g + T_l} \quad \text{(IX/1.2.3-23)}$$

This property is used to measure the local void fraction. From the volume/area, void fraction can be arrived at by moving the probe in different positions, a mapping of the void fraction distribution in a given area/volume in a conduit. Thermal conductivity, electrical conductivity, and optical properties are mainly used in probes for local void fraction measurements. The choice of physical properties listed above depends on the application and type of substance to be investigated. When using conductivity or optical probes in two-phase flow, one phase has a *significantly different* conductivity (electrical/thermal) or refraction index, respectively. Needle probes can be single-tip/double-tip, or even multiple-tip designs based on application requirements. While single tips can be used for gas fraction, and bubbling frequency; double-tip probes allow measurements of bubble velocity, mean bubble chord length, and time-average local interfacial area [11]. Multiple-point probes are capable determining many parameters such as other components of dispersed-phase velocity irrespective of bubble shape, diameter, and direction. However, in multipoint tips, on account of bulky tips, the hydrodynamic interaction between bubbles and the probe should be taken into consideration and also data analysis becomes complex.

- *Optical probe:* In an optical probe, there will be one source of light—a lamp—and one set of detectors which could be a phototransistor, as shown in Fig. IX/1.2.3-5A. With the help of optical fiber, the light beam

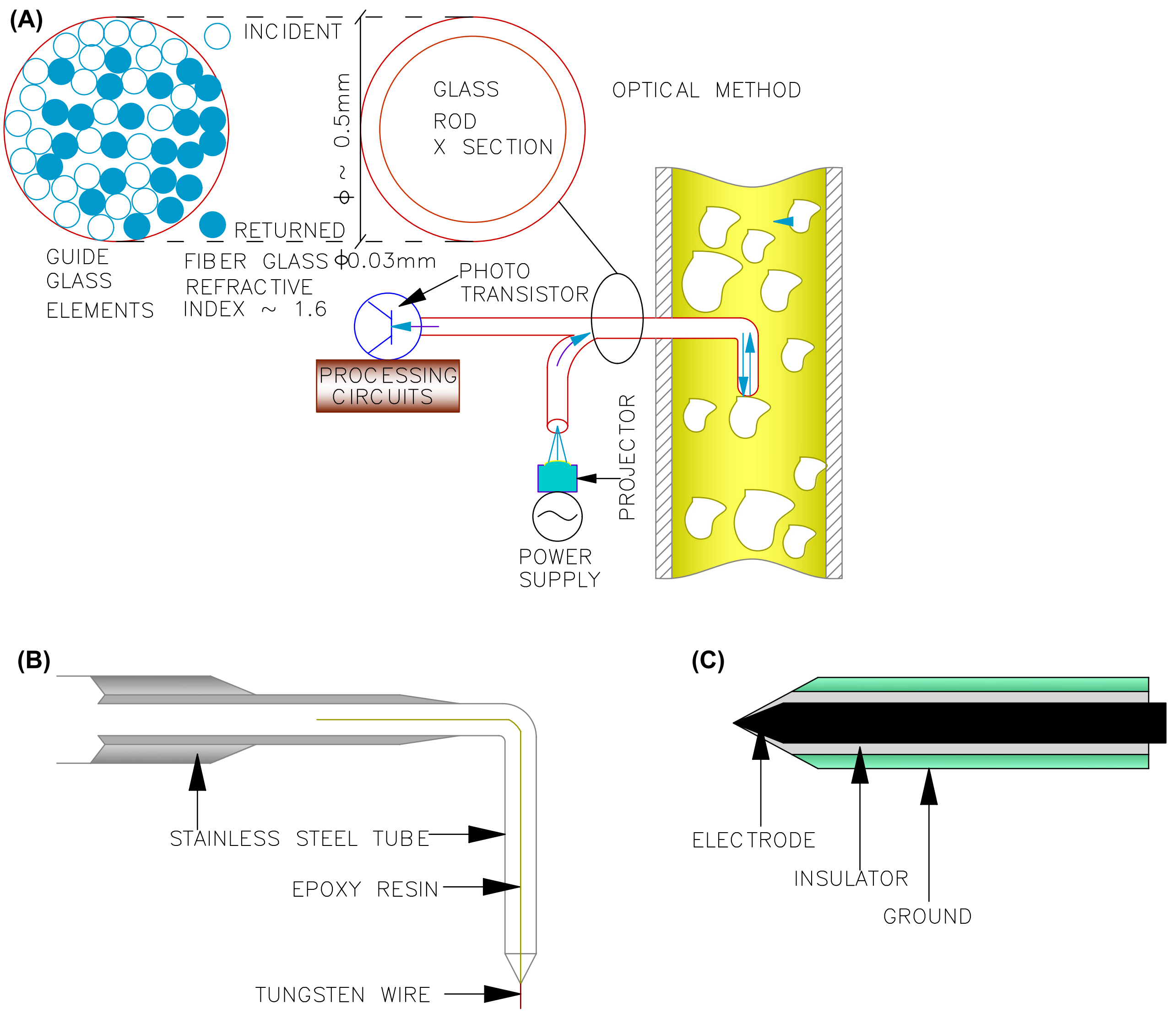


FIGURE IX/1.2.3-5 Needle probe for void fraction (mapping). (A) Optical needle probe. (B) Thermal needle probe. (C) Electrical needle probe.

is guided along the probe, up to its tip. Depending on the phase present at the probe tip, the light is transmitted through the medium or reflected back. When the tip is submerged in liquid, i.e., liquid phase, following optic laws, the tip transmits the light beam away. On the other hand, when the probe is in the gas phase, light from the tip of the probe is not released (and reflected to the phototransistor). An optoelectronic device (phototransistor) delivers an analog output signal in proportion to the received light intensity.

- *Thermal conductivity probe:* In this method the probe somewhat acts like a thermal switch. When the probe is in the liquid phase, thermal conductance between the probe tip and the tube wall is established. In contrast, when the probe is in the gas phase, the thermal conduction path is broken. Therefore, with thermal anemometers, it is possible to make simultaneous measurements of local temperatures and void fraction. A typical thermal conductivity probe has been depicted in Fig. IX/1.2.3-5B.

- *Electrical probes:* Like a thermal conductivity probe, an electrical conductivity probe also acts like a switch. The probe can be either a direct current or alternating current excitation type. Typical electrical conductivity has been detailed in Fig. IX/1.2.3-5C. When the phase at the probe tip is electrically conducting, a current flows from the inner excitation electrode to the grounded external electrode. In the case that the phase at the probe tip is nonconducting the circuit is open and there is no current circulation. Such current is normally converted in a signal processing unit, to give an indication of phase. In a signal processing unit the signal is conditioned and digitized for communication to another system and transmission.

Further details including application areas of needle probe has been covered in Section 3.5.0 also. Apart from these there are a few other methods, such as imaging by ultrasonic and miscellaneous technologies, which are detailed in subsequent discussions. We now look for various systems for two-phase flow measurements under section sensing and sensors for two-phase measurements.

1.2.4 TWO-PHASE FLOW SENSING AND SENSORS (CORIOLIS MASS FLOW, US, PIV, AND LDA)

There are many technologies — Some of them already discussed, in use for multiphase, specifically two-phase, flow measurements. Apart from these and conventional instrumentation techniques there are noninvasive techniques that are used. Out of main noninvasive techniques for two-phase flow measurement, the optical, radiation, and ultrasonic techniques are major techniques. The main optical techniques are particle image velocimetry (PIV) and laser Doppler anemometry (LDA). In these two techniques the pipe has to be transparent. However, ultrasonic techniques do not have such a restriction. In this section brief discussions are put forward on various measuring techniques used in a multiphase (two-phase) flow-measuring system. Multiphase, and for that matter two-phase, flowmetering is always problematic for the majority of flow technologies deployed for single-phase flow measurements, especially for volumetric measurements. Major problems come from the presence of air/gas. Two-phase means a mixture of a gas and a liquid and is not restricted to mixtures where the gas and liquid are of the same chemical composition. An example will explain the issue of why the presence of gas can aggravate errors in measurement. If there is, e.g., 4% gas present, then even with zero velocity error when (say vortex, turbine, ultrasonic, etc.) velocity is multiplied by cross-sectional area there will be an error of 4% in the volume flow output. We start the discussions with the use of a Coriolis mass flow meter in two-flow measurement.

1. **Coriolis mass flow meter:** Since a Coriolis meter gives high accuracy and measurements are independent on many process conditions, such as pressure, temperature, etc., people like to deploy Coriolis mass flow meters (refer to Section 2.0.0 of Chapter VI), for two-phase flow measurement also. Under certain conditions it can also give better results. Coriolis mass meters are not affected by GVF in the same way as other flow technologies. Therefore, highly accurate (0.1%) Coriolis meters with a flow tube and transmitter are often used in two-phase flow measurements. For *certain* flow regimes and with the presence of *entrained* gas, Coriolis meters are capable of producing output overstating the desired liquid mass mainly, when the mass of entrained gas is usually inconsequential (mass of gas is relatively small compared to the mass of the entire fluid stream). This could be true for highly viscous fluid with GVF of around 50%. However, GVF has varying effects on mass flow measurement accuracy depending upon several process conditions. Therefore, the above statement cannot be considered in a generalized way. Detailed discussions on Coriolis mass flow have already been presented in Section 2.0.0 of Chapter VI. Like most other flow

technologies, it is very difficult to predict the % volume of a gas two-phase fluid, with which can be measured by a Coriolis meter accurately. The difficulties come from various corners, such as process conditions (e.g., distribution of the gas, operating pressure, viscosity), installation type, type of entrapped air, etc. We now take up these issues.

- *Entrapped air—Empty start batch:* Entrained air can be encountered when in a process, before the start of the process the line needs to be purged or evacuated, or purging after the last fill operation for example. In such a situation the meter faces an empty start. Meters available in the market which can withstand this situation, so meter selection is important.
- *Continuous entrapped air:* If the seal of the pump has a leakage, a similar situation will be faced when there is air in the liquid continuously. New-generation meters are available to meet these challenges.
- *Vibration dampening:* Coriolis meters always try to total mass (liquid and gas) while traveling through the measuring tubes. However, they cannot always do so (e.g., due to high gas content or low viscosity), then the measuring tubes will be dampened out and stop vibrating.
- *Flow pattern:* We have seen earlier that with changing flow rates physical distribution changes result in various flow patterns. In addition to this, a change in viscosity can altogether change the physical distribution and interaction of the two phases. This could affect the meter.
- *Slug flow:* In slug flow liquid rushes into gas cavities that are not flowing at different speed. This is bound to cause dampening the in sensor tube vibration and hence cause deviation from design frequency and tube amplitude. When the energy to the tubes (induced by the driver coil) reaches intrinsic safety limit, there will be driver coil saturation. Some manufacturers attempt to use electronics to solve this. However, for continuous slugging process, meters cannot be used directly without an air eliminator. According to micromotion, "Especially with slug flow condition, the installation can be very important" [12].
- *Pressure drop:* Pressure drop in a Coriolis meter is a burning issue. Meters with curved tubes need to have a larger meter to overcome this, especially when slug flow is anticipated. From here another important issue is that the *geometry* of tube has also a role to play.
- *Tracking:* The tracking of the flow tube by the transmitter should be well responsive, with low latency. When there are rapid changes in damping, amplitude, frequency, and phase on the sensor signal for any reason, e.g., due to a change in the flow pattern, it is essential that such changes are well tracked by the transmitter to generate an appropriate drive signal. If there is much dead time, i.e., slow response for drive control update rate, the flow tube may stall as changes were not attended to. Also, inaccurate tracking leads to a phase shift between the input and output, leading to forced oscillation. All these will lead to a poor response from the meter. This also ensures amplitude stability and noise filtering.
- *Drive gain and energy saturation:* There is an absolute limit on the energy for any intrinsically safe flow tube. The default amplitude of oscillation at times cannot be sustained, especially in the case of slug flow mentioned above. Many think that this is the main reason for flow tubes stalling. Some positive feedback drives cannot exceed a maximum drive gain limit due to amplifier saturation and any further rise in drive current to compensate for the increased damping is not possible, due to drive saturation [13]. Therefore, on account of drive saturation, there will be a *drop* in the drive signal output.
- *Applicable standard:* When used for liquid measurement (fiscal purposes) applicable

standards are ISO 10790 and 6551—Latest version; API:MPMS 5.4 thru' 5.6 latest version. There have been a number of research work toward this. As a result, improved versions are available now. There are meters with dual drives, which can provide better performance in an intrinsically safe condition. These instruments promise to provide rapid dynamic response, faster updates, etc. They may be capable of meeting the challenges discussed above. Interested readers may refer to the ISA conference paper [12] for further details.

2. **Ultrasonic technique:** Ultrasonic techniques are nonintrusive and noninvasive, without restrictions on the pipe type, nor do they not need safety care for the operators (e.g., from gamma radiation). As these are attached from outside the pipe they can be used in high-pressure and high-temperature flows and can also be used in opaque fluids.
   - *US methods:* There are several ultrasonic methods for two-phase flow diagnostics, namely the pulse-echo, transmission, and Doppler shift methods. The Doppler shift method has a relative advantage when applied in low void fraction liquid flow velocity measurements. Therefore, these are more popular. Also, in connection with slurry flow, it is seen that these are used for liquid—solid mixture flows. Pulse echo techniques as frequently used for voids in structures are also used for gas bubble velocity measurements. Case studies show that the echo technique – Ultrasonic velocity profile (UVP) method has been successfully applied to air—water bubble flow measurement. US mesh sensing and US tomography are also used for multiphase flow measurements.
   - *US mesh sensor:* Visualization of two-phase flow is done with the help of an ultrasonic mesh sensor. The system consists of two groups of wave guides. The first group is responsible for irradiation of acoustic waves in a two-phase medium. The second group receives the signal sent through the medium. Based on the presence of gas in the medium, attenuated ultrasound will reach the receiver wave guide, where it is transformed into an electrical signal. Based on data acquisition in the electronic signal processing unit an image is developed which takes into account the GVF.
   - *Ultrasonic tomography:* Ultrasonic tomography can provide images of two-component flows, quantitative and real-time data on chemical media. This noninvasive method can give an idea about an insight into the actual process and it is possible for online monitoring control of the system. An ultrasonic sensor, which is sensitive to the density of sound changes, has the potential for imaging component flows, such as oil/gas/water mixtures [14]. For ultrasound the relation between acoustic impedance (Z) of medium with density ρ, and the velocity of sound c is

$$Z = \rho c. \qquad \text{(IX/1.2.4-1)}$$

With reference to the discussion on US flow metering theory in Chapter V (Section 6.0.0), it is known that there are two types of ultrasonic signals, i.e., a continuous signal and the pulsed signal. In a continuous signal there will be a continuous impact on the crystal, whereas in the pulse type, the interval time between transmission and reception signal are estimated. A typical US tomography has been depicted in Fig. IX/1.2.4-1.

In Fig. IX/1.2.4-1 there are eight pairs of ultrasonic transducers (transmitter—receiver sets) arrayed circularly around the vessel used for measurement. In Fig. IX/1.2.4-1 only eight pairs are shown but there could be more based on the requirement. In the transmission-mode method and the fan-shaped beam projection technique, the ultrasonic transmitters will transmit pulses through the process vessel to the point of interest [14]. Through a software scanning routine, each transmitter gets excited to emit two cycles of tone burst. On the divergence

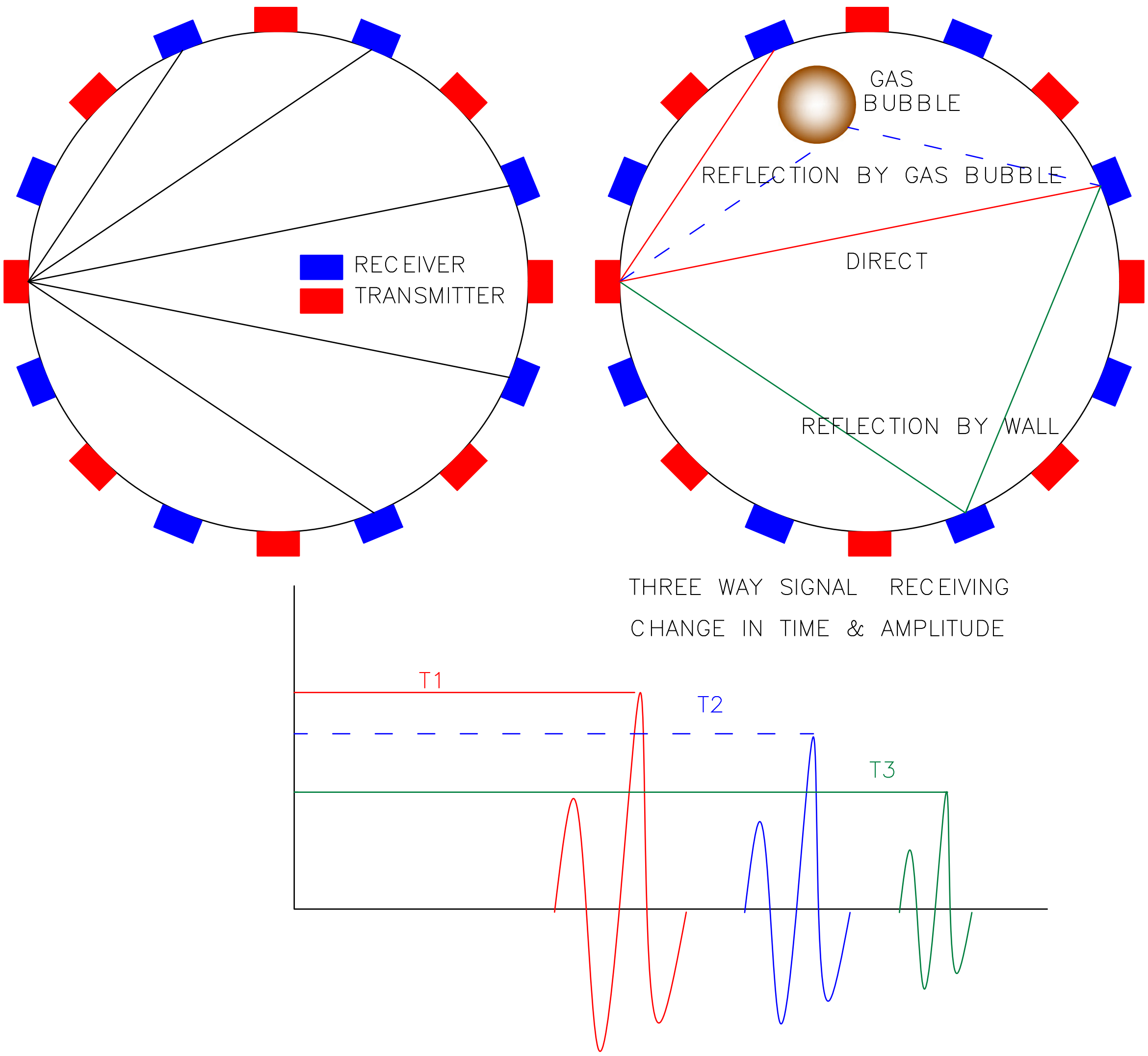


FIGURE IX/1.2.4-1 Ultrasonic tomography.

angle, the transmitter signal will cover a number of receiving transducers as shown. We now look into the details of a transmission—receiver set. As seen in Fig. IX/1.2.4-1 there are three cases of signal receptions, like first- direct transmission, where amplitude will be the highest and the time of peak is detected will be lowest. Second- when there is a gas bubble then the amplitude will be lower and due to reflection the time for detection will be more. The third case will be reflection by the wall. The system consists of a number of signal-processing units comprising a microcontroller to control the projection. Received signals are processed and sent to the comparator and there after processed signals are sent to the data acquisition system to reconstruct the image. The measuring system requires suitable software support.

Another technique of imaging to study multiphase/two-phase fluids is particle image velocimetry (PIV). This technique has been known for a long time but use of the technique in the study of two-phase flow is not as long established. In the next section this will be discussed.

3. **Particle image velocimetry (PIV):** Individual phase/component velocities can be determined easily in two-phase/multiphase flows when the phases are separated prior to the analysis. The

continuous liquid velocity field can be captured using well-established, standard particle image velocimetry (PIV) techniques to obtain instantaneous velocity fields in a two-dimensional plane of finite thickness. PIV is extendable to three dimensions with special considerations. PIV measures the velocity data of a particle-seeded flow field within either a two-dimensional plane or three-dimensional volume. It accurately tracks micron-sized seeds suspended in the flow path. These particles have certain physical properties so that they accurately follow the flow path lines and respond to accelerations in the flow. Other phases can be bubbles with various diameters in the liquid phase or liquid droplets in the continuous gas phase. With PIV it is possible to get information on the concentration and size of the suspended phase and their distribution in space. PIV is a complex system which takes into account statistical correlations, Fourier transformation, and fast Fourier transformation for PIV data processing and analyzing of the image to interpret multiphase flow. Only the basics of PIV have been included in this book, eliminating intricate details to limit the space and size of the book. The discussions start with the questions: what is PIV and why PIV?

- *What is PIV and why PIV?:* PIV is a nonintrusive method of flow visualization (imaging system). In this system, particles of required specification (elaborated later) are introduced into the fluid of the measuring system so that they are in suspension in the fluid. The PIV system basically uses the help of the illumination of these suspended particles which follow the fluid flow, to study the properties of the flow of the medium, including its structure. PIV tracks the bulk movement of particles within an interrogation area and studies the same thoroughly to arrive at fluid properties through statistical correlation and numerical analysis. *PIV* is a seeding method to study the whole field to obtain instantaneous flow details of the flowing medium with structural details, so it is often used for studying multiphase flow properties also.
- *PIV assumptions and particle properties:* The entire measurement system stands on a few assumptions and particle properties indicated above. These assumptions include: Homogenized distribution of tracer particles which should follow fluid and uniform displacement of particles *within* the interrogation region. Also, it is necessary that the particles, which should *not* influence fluid flow, are *small* enough (diameter of 1−10 μM) and be easily visible.
- *PIV hardware:* The major hardware components of the PIV system are laser and allied optical system including camera and imaging system, and other components, namely, tracer particles, light source and light sheet with allied optics, camera measurement system, data acquisition, computation, and communication system.
- *PIV software:* Major software includes: controlling algorithms, interrogation, computational software, data acquisition software, communication software.
- *Brief principle of operation:* PIV is a nonintrusive method for imaging of multiphase flow, in other words, flow visualization as shown in Fig. IX/1.2.4-2A. It is very important to note that PIV is different from another technique, particle tracking velocimetry (PTV), where each particle is individually tracked, as shown in Fig. IX/1.2.4-2B to show the distinguishing features. The PIV working principle is based on tracking the illumination of particles suspended in the fluid. These particles follow the fluid flow so that they can be used to study the properties of flow, such as its structure. Therefore, PIV is a separate technique where the **bulk** movement of particles within an interrogation area is tracked. Therefore, in this method the desired position of particles is accurately recorded. It is important that the position of the particles does not change during the illumination. That is, the light has to be *short*, therefore, the laser light is continuous, but the laser sends *pulses*. It is necessary to record the position of the particle [15]. In this method the initial and final

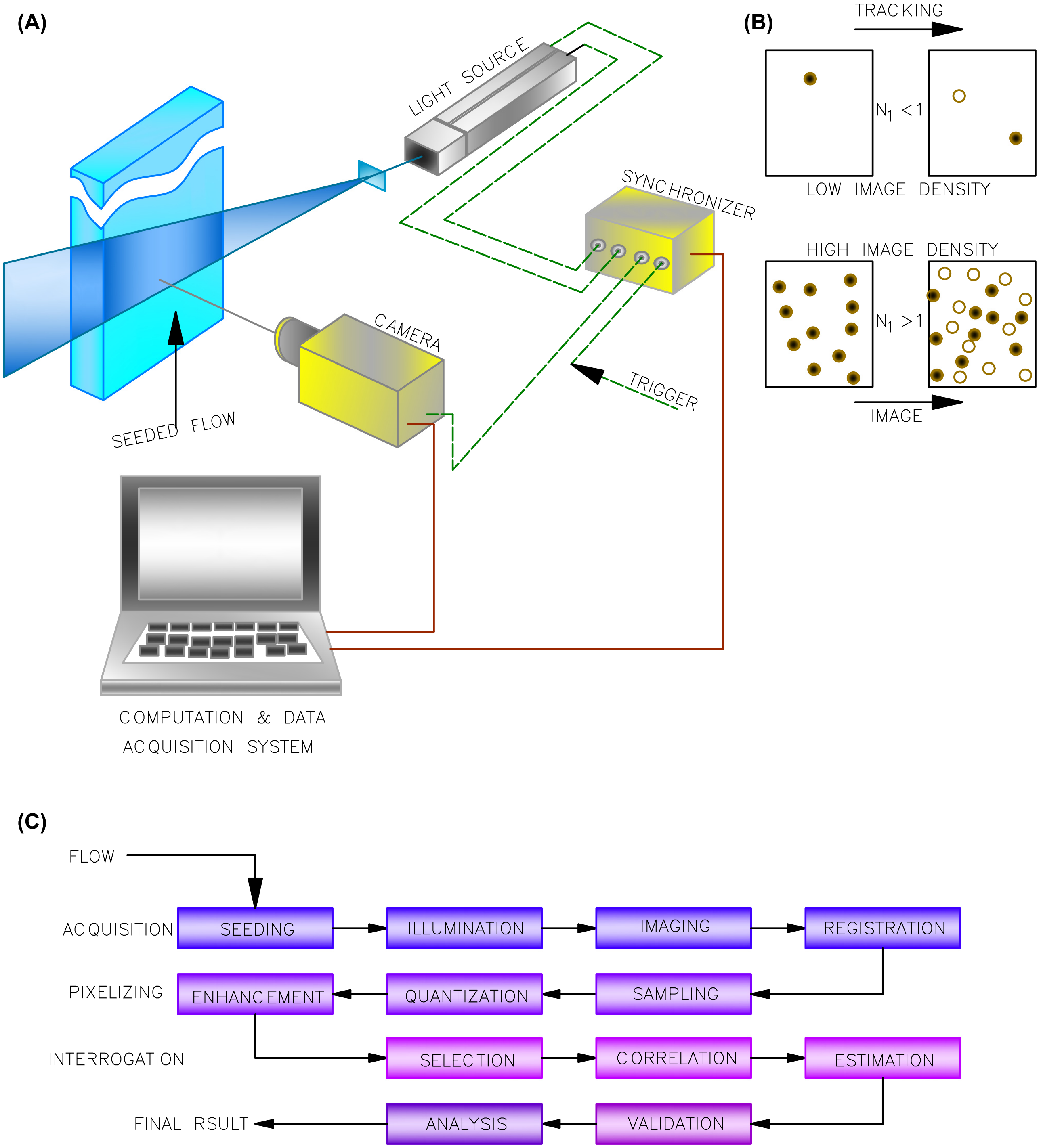


FIGURE IX/1.2.4-2 PIV details. (A) PIV principle. (B) Velocimetry types. (C) PIV steps.

positions of the particle are traced and recorded. There are two ways these positions are recorded, i.e., the individual and double-exposure methods. A comparison of both methods has been presented in Table IX/1.2.4-1. With the help of a camera, two successive light pulses (small differential time) are captured for studying the particle movement due to flow. This double-exposed image provides a 2D picture of the

TABLE IX/1.2.4-1 Comparison of Exposure Types

Single Exposure	Double Exposure
Fast data transfer or cross-correlation camera	No need for faster data transfer
Cross-correlation	Auto correlation
No directional ambiguity	Directional ambiguity
Small displacement detectable	Small displacement nondetectable

displacement record of the particle. Various steps involved in the system have been depicted in Fig. IX/1.2.4-2C. Therefore, there will be a step to pixelizing, where PIV images are sampled and quantized, i.e., the interrogation spot (IS), which is so chosen that it can include a good number of particle image pairs but should not be large enough that there will be more than **5%** velocity variation across it. Captured images are then investigated through correlation. Statistical analysis of correlation is used to determine the relationship between the two processes or values. The output of the correlation when evaluating PIV images is the average displacement of all the particles in each reference in the evaluation area. Based on the type of exposure, correlation techniques are different. For an individual-exposure method the cross-correlation method is used, whereas for double-exposure method on a single frame, autocorrelation is used. In order to gather knowledge about the distribution function, i.e., the characteristic feature of the distribution, it is necessary to express the time-dependent signal using harmonic functions, so that it is required to change the signal from a time domain to a frequency domain. The transformation of the signal transfer time domain to the frequency is carried out by Fourier transformation in varied dimensions. In order to determine the range of signal samples from the sample spectrum, fast Fourier transform, which is an algorithm for calculating the discrete Fourier transform and its inversion, is utilized (for details a standard book on Fourier transformation may be referenced).

- *Interrogation cell:* This is a small area under investigation, around 1.6 × 1.6 mm (32 × 32 pixels) [16], where correlation provides an average displacement vector. With this the discussions on PIV are concluded and we now move on to an overview of LDA.

4. **Laser Doppler velocimetry/anemometer:** Two-phase velocity measurement and getting a distribution pattern of gas and fluid laser Doppler velocimetry (LDV), also known as laser Doppler anemometry (LDA), can also be adapted. Here also, the measurement principle depends on particle theory, i.e., seeding of the particle. It is worth noting that LDA is a commonly used single-phase flow measurement, but its use in two-phase applications is also noted from a study of the literature. LDA is not really a new to readers because in Chapter V it was discussed at length for the measurement of velocity in single-phase fluid. In principle, Eq. V/7.3.2-1 should be equally applicable for cases in which more than one phase is present, even if the scattering particles or bubbles are larger than the measurement volume (Durst and Zare, 1975). On account of differences in light-scattering characteristics between relatively small seed particles in the continuous liquid phase and larger transparent bubbles, which comprise the dispersed gas phase, there may be difficulties associated with LDV/LDA. From a report prepared by GE for US department of Energy [17] it is revealed that the use of LDV in gas—liquid flows is difficult, mainly on account of:

As the concentration of gas—liquid interfaces increases, the incident laser light is increasingly scattered, so an LDV measurement volume can only be formed for very short time periods. This problem becomes more pronounced with increasing void fraction and/or test section fluid thickness.

> *When a Doppler-shifted event occurs in the measurement volume, the scattered light transmission path and the optical and data acquisition configuration must be such that LDV signals due to bubbles and seed particles can be detected and separately analyzed.*

However, many investigations and results showed that LDA can be applied for two-flow applications also. Laser Doppler velocimetry is a nonintrusive experimentation technique for the investigation of fluid flow in gases and liquids. As already discussed in Section 7.3.0 of Chapter V, measurements are based on the signal produced by a particle passing through a volume of interference fringes. As in PIV, in the case of LDV the selection of particle size and type is important as seed particles need to closely follow the flow to provide representative velocities. The frequency of particles to flow fluctuations is dependent on the same. In order to measure the velocity of the fluid phase, only the small particles should be examined, otherwise its frequency response will not be good. In this method, Gaussian functions are used to calculate the amplitude. The data are stored for further burst analysis. Here autocorrelation is used to establish the correlations.

There are many other types of measuring technologies available, such as various classes of tomography, etc. These will be discussed at length in Section 3.0.0, where various measurement principles are discussed. Now we give a short overview of wet gas metering and water cut metering.

1.2.5 WET GAS METERING

This discussion starts with reference to Fig. IX/1.2.5-1A, where it is seen that there are basically two parts, one is gas moving with higher velocity and occupying greater volume, and the other part is liquid. Liquid, again consisting of water and hydrocarbon, is represented in the figure as "oil" [so, oil may represent any hydrocarbon (HC) for that matter, as shown in the figure].

As the name signifies, it represents mainly those cases where interest in measurement is in the amount of gas flowing. It is guided by the potential monetary value involved, e.g., gas condensate. Saturated steam and the presence water is also an example of wet gas. This means that any humid gas (or vapor) has been accepted as wet gas without any quantitative definition. Usually ***GVF > 90*** at least (many consider GVF > 95%) at the actual operating condition has been considered as wet gas. The term wet gas is mainly associated with natural gas production from wells where it is not found in a dry state but found with small quantities of liquid. From a natural production point of view "wet gas" refers to the presence of hydrocarbons (HC) heavier than ethane, which tends to condense at reduced temperature and pressure conditions. Generally, in oil and gas fields "wet gas" refers to the processes where the proportion of liquid phase is no greater than about 5% by volume (i.e., GVF is greater than 95%). Water vapor condensing to water often is found as an additional component of wet gas. Therefore, strictly speaking, wet gas in a natural well should be viewed as a three-phase stream consisting of gas, condensate (other liquid), and water. A common simplification is to consider only two phases, gas and liquid, which at a later stage in the production process can be distinguished. It is recommended that in this connection Subsection 3.4.2.4 of Chapter I should be referenced to complete the discussions. There the classification of wet gas meters, as per Lockhart-Martinelli number/parameter X, has been discussed.

In this section brief discussions are presented on wet gas measurement issues rather than wet gas measurement devices, which are covered later in this chapter.

1. **Lockhart-Martinelli number/parameter X:** In the above discussion, we mentioned that wet gas is generally considered so when GVF >90−95 at least at the actual *operating condition*. The operating condition

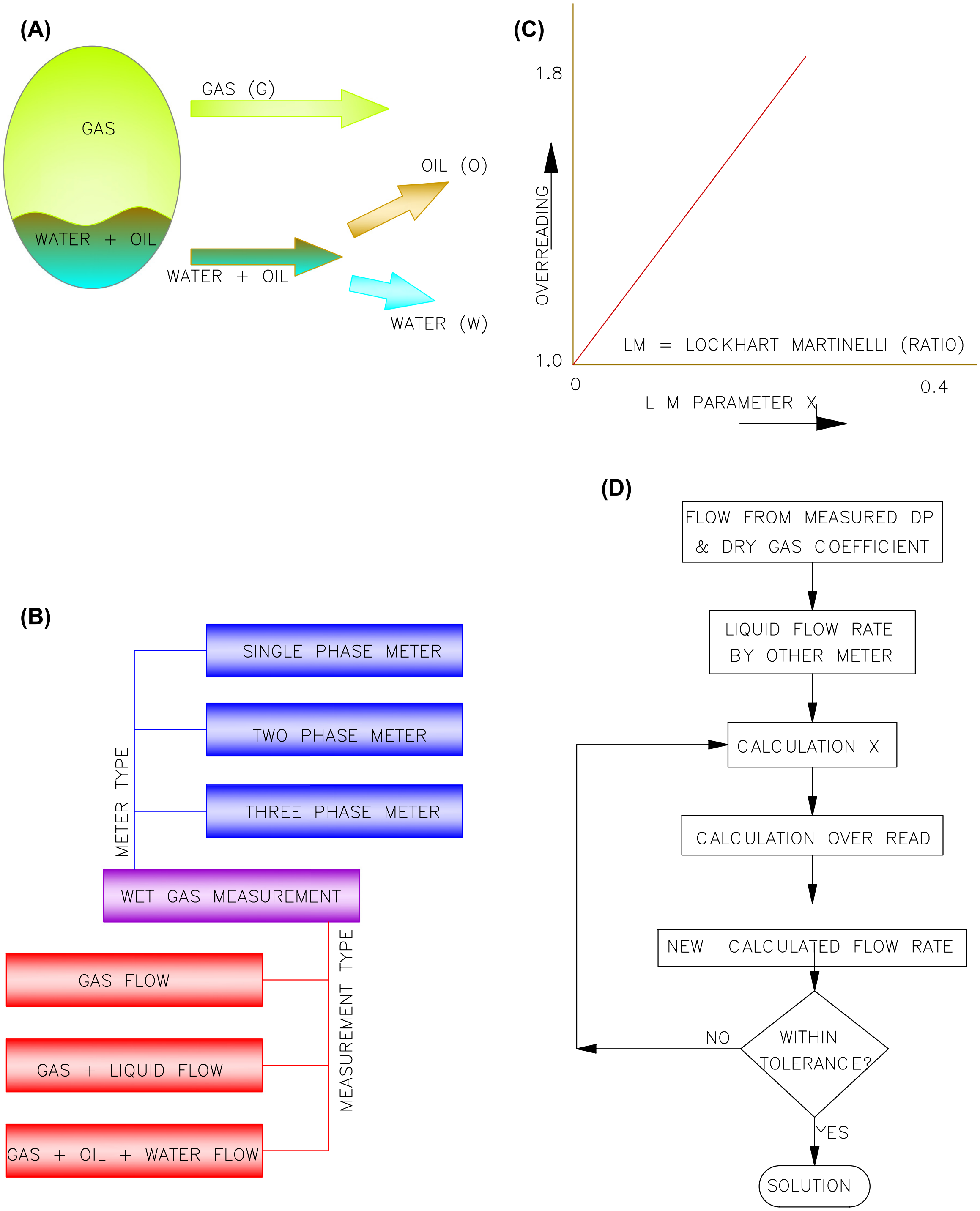


FIGURE IX/1.2.5-1 Wet gas meter details. (A) Wet gas in pipe. Oil−hydrocarbon (HC). (B) Wet gas meter types. (C) Over-reading response. (D) Wet gas calculation steps. *(D) Developed based on an idea from An introduction to wet-gas flow metering, Good Practice Guide, National Measurement System, TUVNEL. http://www.tuvnel.com/_x90lbm/An_Introduction_to_Wet-Gas_Flow_Metering.pdf.*

is a problematic issue in the sense that when the operating condition changes there may be more appreciable changes in the gas part than in the liquid part, e.g., gas density changes with pressure but not that in liquid. Naturally, the situation changes when there is a change in the operating condition, e.g., when gas is transported from a reservoir at high temperature and pressure to where it is brought ashore. It is needless to say that if such changes are not taken care of then there will be errors in the reading of the liquid content in gas. To take care of this one may use the unitless Lockhart-Martinelli number/parameter illustrated in Fig. I/3.4.2.4-1. Therefore, normally the wetness or liquid loading of the gas is defined, taking into account the Lockhart-Martinelli number/parameter. In fact, wet gas meters are classified as per Lockhart-Martinelli number/parameter (refer to Subsection 3.4.2.4 of Chapter I). The Froude number is another dimensionless number (refer to Chapter III) and is also used to express the liquid or gas phase velocity.

2. **Meter category:** As shown in Fig. IX/1.2.5-1B, wet gas meters can be categorized in two ways:
   - *Measurement type:* In this part one has to judge the importance and purpose of the measurement. When there will be a low liquid content or the value of the liquid is not there only gas metering will suffice. Considerations are whether it is for gas flow only, gas and liquid flow, or individual flow requirements.
   - *Meter type:* This basically comes as a corollary of the above, i.e., whether the meter will be a single-phase (after separation), two-phase, or three-phase meter. The first is to physically separate the streams then individually metering them using conventional instrumentation. The second is to use a single-phase meter (typically DP elements) on the wet gas stream, and compensate the reading for the errors from the effects of wet gas. The third approach is to develop (costly) truly multiphase meters.
3. **DP measurement and over-reading:** DP metering is only possible when wet metering is used as a gas meter, i.e., a single-phase meter. In DP measurement over-reading is an important phenomenon. We know that the DP meter flow rate is proportional to the square root of measured DP. On account of liquid there will be a higher pressure drop. Therefore, the direct use of the meter reading will introduce a high error in the measurement as the meter would tend to over-read. So what is over-read?
   - *Over-read:* Over-read can be defined as a ratio:

$$\text{Over} - \text{reading} = \frac{\text{Gas mass flow rate in wet gas condition}}{\text{Gas mass flow rate in dry gas condition}} = \sqrt{\frac{\text{DP in wet gas}}{\text{DP in dry gas}}}$$

   It is well-known that such devices over-read compared to dry gas calibration; equations to correct the reading are available if the degree of gas "wetness" is known. Therefore, when over-reading is plotted against Lockhart-Martinelli number/parameter X, which takes into account density with flow rate for liquid and gas, one would expect to get a curve as shown in Fig. IX/1.2.5-1C. Over-read in DP measurement depends heavily on:
   - Gas density;
   - Flow element beta ratio;
   - Gas velocity;
   - Gas−liquid density ratio;
   - Liquid phase properties (e.g., density, viscosity, etc.).

4. **Meter correction factors:** From discussions in Chapter II, it has been noted that DP measurements by flow elements are affected by a number of factors listed below:
   - Geometry;
   - Gas velocity;
   - Flow pattern;
   - Pressure and temperature;
   - Liquid viscosity;
   - Liquid surface tension.

   Thus, there will be a specific correction factor for each of the flow element types. These are described here:
   - *Murdock correction factor (F_m):*

   $$F_m = \frac{1}{1 + M\cdot X\cdot \varepsilon\cdot \left(\frac{C_g}{C_l}\right)} \quad \text{(IX/1.2.5-1)}$$

   where, M is operator's entry (1.26 default), X = Lockhart-Martinelli number/parameter, ε = gas expansion factor, C_g, C_l coefficient of discharge for gas and liquid, respectively.
   - *Chisholm correction factor (F_{ch}):*

   $$F_{ch} = \frac{1}{\sqrt{1 + KX + X^2}} \quad \text{(IX/1.2.5-2)}$$

   where $K = \left(\frac{\rho_l}{\rho_g}\right)^n + \left(\frac{\rho_g}{\rho_l}\right)^n$, where ρ_g and ρ_l are densities of gas and liquid, respectively, X mentioned above n is the operator-entered parameter (normally 0.25).
   - *De Leeuw correction (F_{Dl}):* De Leeuw correction factor F_{Dl} is the same as the Chisholm correction factor above, but the value of n varies with Froude number F_r (refer to Chapter III).

   n = 0.41 for Froude number $F_r < 1.5$ and $n = 0.606 \times \left(1 - e^{-0.746\times F_r}\right)$ Froude number $F_r > 1.5$.

   Normally for an orifice F_m and F_{ch} are used. For a Venturi, De Leeuw correction F_{Dl} is used. For a V cone some correction factors are available but, on account of the proprietary in nature it is better to consult the manufacturer.

5. **ISO TR11583 correlation:** It is important to take note of the following as per ISOTR 11583: Here the Froude number is represented by Fr_g for gas.
   - *Discharge coefficient:*

   $$1 + 0.0463 \times \exp(-0.05Fr_{g,th}) \min\left(1, \sqrt{\frac{X}{0.016}}\right) \quad \text{(IX/1.2.5-3)}$$

   where $Fr_{g,th} = Fr_g/\beta^{2.5}$ and $Fr_g = \frac{U_{Sg}}{\sqrt{gD}} \times \sqrt{\frac{\rho_g}{\rho_l - \rho_g}}$, and D is the pipe internal diameter, and U_{Sg} is the superficial gas and liquid velocities:
   - *Over-reading coefficient:*

   $$(\varnothing_g)^2 = 1 + CX + X^2 \quad \text{(IX/1.2.5-4)}$$

   where C is given by $C(K) = \left(\frac{\rho_l}{\rho_g}\right)^n + \left(\frac{\rho_g}{\rho_l}\right)^n$

   n = max of $\{(0.583 - 0.18\beta^2\ 0.578 \times e^{-0.578Fr_g/H})$ and $(0.392 - 0.18\beta^2)\}$; H = 1 for hydrocarbon; 1.35 for water at ambient T°C.
   - *Mass flow rate:*

   $$\dot{m} = q_{mg} = C_d\cdot\varepsilon\cdot\frac{1}{\left(1-\beta^4\right)^{1/2}}\times\frac{\pi d^2}{4}\times\frac{\sqrt{2\rho_g\cdot\Delta P_g}}{\varnothing_g} \quad \text{(IX/1.2.5-5)}$$

6. **Pressure ratio method (for X):** By now the reader should be aware that pressure drop across the flow element is partly recovered downstream of the restricting element. From the discussions on DP elements in Chapter II, it is clear that such recovery is more applicable in Venturi than other DP elements. Also, the position, downstream, at which such recovery will be made, is more or less defined for the medium. In wet gas conditions, on account of the presence of

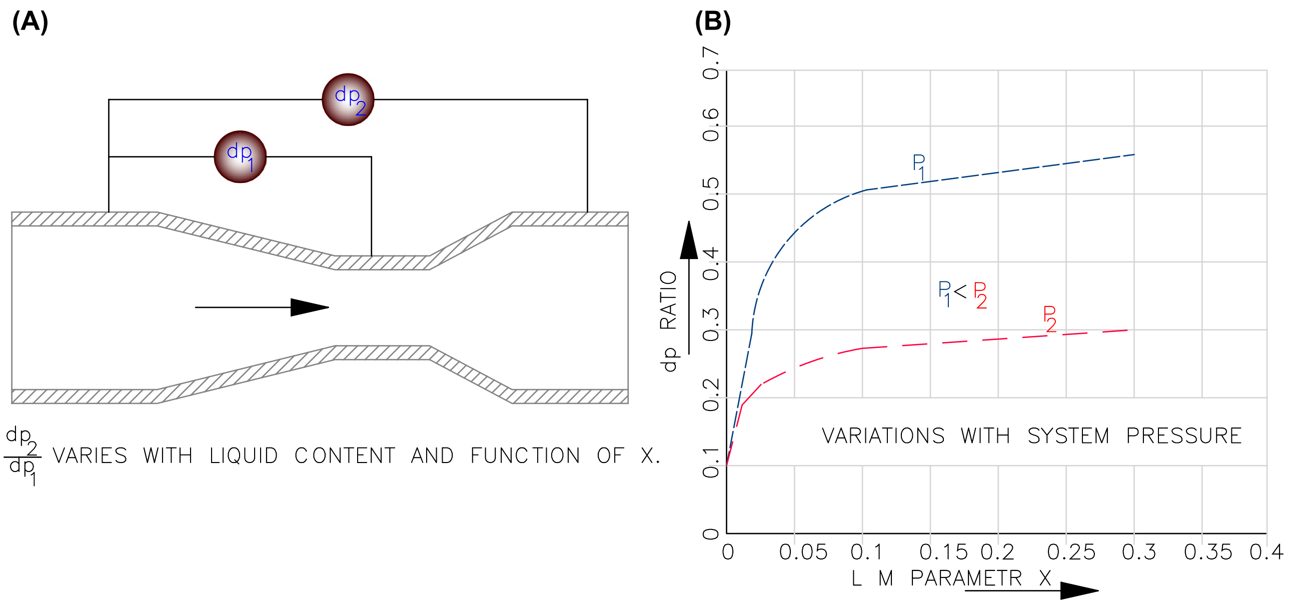


FIGURE IX/1.2.5-2 Pressure loss ratio for wet gas metering. (A) DP ratio for liquid content. X = Lockhart-Martinelli parameter. (B) DP ratio vs. X.

liquid, there will be less pressure recovery. In this method such a difference in recovery is exploited to measure the liquid fraction. The method involves using an additional pressure tapping downstream of the Venturi tube to provide a measure of the overall pressure loss, dp_2, as shown in Fig. IX/1.2.5-2A. As shown in the figure, in a Venturi, the overall pressure loss (dp_2) and differential pressure (dp_1) are used to calculate the pressure loss ratio (dp_2/dp_1). The pressure loss ratio (dp_2/dp_1) corresponds to the liquid content and is sensitive for low values of Lockhart-Martinelli parameter X. In this connection, Fig. IX/1.2.5-2B may be referred to. The discussions have been presented here for a Venturi, but can be utilized for an orifice plate also. Its use is limited to calculating values of X up to maximum values of approximately 0.05. It should be noted that the method is known to be affected by the system pressure [17].

7. **Non-DP instruments:** As stated in the initial discussions in this section, the DP method is *mostly* used for wet gas measurement (treating as a single phase without separation). This means that there is room for use of other metering options also. However, in applying such instruments knowledge of the effect of the presence in liquid in gas on the meter is required. All other meters, such as turbine meters, ultrasonic meters, vortex meters, and Coriolis mass flow meters can be deployed for measurement of gas in the presence of liquid. Discussions on the restrictions on Coriolis mass flow meters have already been covered in Subsection 1.2.4.1 above.
8. **Two/three-phase wet gas metering:** There are various meters in the market specifically meant for wet-gas flow measurement for the meter to take care of both liquid and flow rates directly. Most of these measuring methods involve two types of measurements, with different technologies. One of the simplest principles for measurement of both liquid and gas flows is to use two DP devices in series, which provide the same flow rate for dry gas but each device has a different over-reading response when liquid is present. The *difference* in over-reading response can be exploited and correlations are then

applied to the data to determine both the gas and liquid flow rates. Some wet-gas metering systems use one differential pressure device in series with another non-DP meter and use the difference in the meter responses to the local wet gas flow conditions to estimate the individual phase flow rates. To get an idea of such a measuring method, Fig. IX/1.2.5-1D may be referenced. Wet gas meters with a description and specification covering various options have been discussed in Section 2.2.0 of this chapter.

9. **Wet gas measurement issues:** There are a number of issues which need to be considered; these are use of a flow conditioner and formation of hydrates. On account of the presence of liquid in gas there will be asymmetrical flow profiles. Therefore, flow conditioners are used upstream, not only to reduce swirl but also to reduce the upstream straight length requirement. Another issue is hydrates, which are solid crystalline structures formed due to the mixture of gas (there may be solids therein) and water at a certain pressure and temperature. Both issues need to be addressed.
10. **Tracer injection method:** The tracer injection method is another way to measure wet gas quantity but this is basically a laboratory-based testing method. A liquid containing fluorescent material, which is solvable in water/condensate, is injected at a measured rate in a pipe through which wet gas is passing. At a distance sufficient (at current flow rate) for liquid to get dissolved, a sample is taken from the pipe for testing in the laboratory to get the flow rate of water as per the following formula

$$F_{water} = (F_{inj} \cdot C_{inj})/C_{sample} \qquad \text{(IX/1.2.5-6)}$$

where F_{water} is the target measurement, C_{inj} and C_{sample} are concentrations of florescent material during injection and at the sample, respectively. F_{inj} is the flow rate of injected material.

Let us now look into another issue of water cut metering, which is also very important in two/multiphase flow metering.

1.2.6 WATER CUT METERING

In its simplest terms, water cut represents the ratio of volume flow of water to total liquid. Therefore, a water cut meter measures the water content (cut) of hydrocarbons as they flow through a pipeline. Only a few details generally applicable for water cut measurement have been indicated here. Details of water cut meters have been given in Section 2.3.0.

1. **Types of instruments:** There are many types of water cut measuring instruments. These include conductivity, capacitance, microwave resonant, and optical (near infrared) types. Of these, the change of permittivity type, i.e., capacitance change type, are most commonly used. Apart from these, water cuts are often measured as part of two-phase flow measurement, utilizing various combined methods, e.g., electrical resistance tomography and electromagnetic flow meter.
2. **Factors affecting measurement:** The following parameters affect the measurement:
   - Density;
   - Salinity;
   - Top cut.
3. **Meter range and uncertainty:** Normally, water meters are available in various ranges with different accuracy levels. Water meters can be classified as low range, mid range, high range, and full range. A brief account of them, along with their performance criteria, has been enumerated in Table IX/1.2.6-1. In this table WØ and OØ represent the water and oil/hydrocarbon phase. Inversion means the point at which oil phases change to water phases and vice versa.

TABLE IX/1.2.6-1 Water Cut Meter Ranges (% WC) With Performance

Parameter	Low Range (%)		Mid Range (%)	High Range (%)	Full Range (%)
Meter range	0–10	0–20	0-inversion	80–100	0–100
Uncertainty	0.04 (0–4 range)	0.04 (0–4 range)	±0.5	±0.6 WØ	±0.5 OØ
	0.1 (>4)	0.1 (4–10 range) 0.2 > 10			±1.0 WØ
Repeatability	±0.02	±0.1	±0.1	±0.3 WØ	±0.1 OØ
					±0.5 WØ
Resolution	±0.01	±0.1	±0.1	±0.1	±0.1

4. **Application areas:** The following are the major application areas for water cut metering:
   - *Upstream:* Well test and production management;
   - *Mid-stream:* Pipeline;
   - *Refinery:* Crude oil feed line and refinery pipeline;
   - *Shipment:* Pipeline;
   - Tank farm and oil terminal;
   - Separation vessel;
   - Pump protection;
   - Multiphase flow measurement;
   - Custody transfer;
   - Crude analysis system.

1.3.0 Multiphase Flow Metering Philosophy and Well Testing

Basically, the philosophy behind multiphase flow measurement lies with separation and the pros and cons have already been covered in the initial part of this section. Typical methods for such alternatives have been covered in Section 3.4.2 of Chapter I. If we recall the initial discussions one would remember that there needs to be a cost–benefit analysis for using MPFM. Of course, in certain cases there are a few advantages of using MPFM. There exists a number of such meters in the market and each of them has been developed and tested for specific purposes. There has not yet been any well-established measurement method which can cater to the majority of applications and that is well tested. On the other hand in reality, there are wide variations in flow regimes and flow characteristics. Therefore, selection of the optimum MPFM with measurement technology best suited for a specific application cannot be overestimated. For such selection the following major steps may be considered as guidance.

1. **Data and information:** Investigate expected flow characteristics and flow regime, where in most cases such information is scanty and inadequate.
2. **Match making:** Investigate if there exists MPFM with a measuring envelope matching with the specific application.
3. **Check uncertainty and duty cycle:** To check if the MPFM in question is capable of continuous duty and can offer performance within the acceptable limit. It is worth noting that the stream of well output varies throughout the life time. Thus suitable provision should be kept so that it can be replaced by another one at a later date—as necessary.
4. **Sizing:** Meter sizing is an important issue, specifically the range and associated uncertainty. The range should be chosen in such a way that it can cover the production rate over a greater period of time, so that it can take care of output variation over the life time (as mentioned above).
5. **Installation:** Due consideration towards the installation must be given, taking into account

adequate test facilities and calibration (and if needed adjustment).

6. **Verification:** Verification during operation is also an important issue, not only for confidence building on measurement but also to ensure that the measurement is within tolerable uncertainty. Testing and verifications often are carried out by comparing the MPFM flow rate and WLR/GVF measurements against some other means/test separator.

1.3.1 METHODS OF MULTIPHASE FLOW METERING

As is clear from the above discussion, the conventional approach is to measure multiphase flow by separation. In most cases two-phase separators are used, however it has been noted that in Norway for the North Sea, three-phase gravity separators are commonly used. On account of the large difference in density between gas and liquid, in the separator, the liquid and gas become separated given enough time, referred to as the residence time. The oil and water will separate due to their immiscibility and the difference in densities and viscosities of the two fluids. So, at the outlet there will be three different fluids, whose flow rates can be measured by using single-phase flow meters as shown in Fig. IX/1.3.0-3. For direct in-line MPFMs the measurements of the individual phase fractions and total or individual phase flow rates are performed directly in the meter magnetic resonance type. VIS type is also an example of the same as discussed in Section 3.4.2 of Chapter I. As mentioned there are a few methods, such as separation, partial separation sampling are a few other methods by which three flows can be measured using different technologies. These are explained with required details here.

1. **Separation:** In the separation method shown in Fig. I/3.4.2-1A, two-phase separation is done to separate gas and liquid. In the gas side, a direct single-phase meter is used to get the volume flow of gas. In the liquid side, the total liquid flow is measured by a liquid meter with the help of one water in liquid measuring meter, e.g., a water cut meter, the fraction of water in liquid is measured. Therefore, with the help of these two flows, an individual component in liquid can be computed.
2. **Partial separation:** In Fig. I/3.4.2-1B, with the help of a wet gas meter, the correct computation of gas flow has been done. On account of the separation of the major gas part it is possible to compute multiphase (basically two-phase) flow metering by a standard two-phase flow meter.
3. **Sampling method:** As shown in Fig. I/3.4.2-1, here a part of the flow is bypassed and to effect the same a restricting device is kept in the main line. The system is well discussed in Chapter I. In this system GLR is basically a two-phase metering, where the gas−liquid ratio and gas and total liquid flow rates are measured. Thus by knowing the water in liquid ratio from WLR (assuming the sample line is a true representation of the main line), one can get compute water and oil flow from data of GLR and WLR.
4. **Technologies:** There have been a number of technologies available for measurements of multiphase flows. As indicated, some measure two-phase flow along with WLR (e.g., a water cut meter) using microwave technologies. Some use wet gas measurement which, as indicated earlier, is a gas meter with corrections for the presence of liquid; DP measurement is a good example for these. Nowadays, a single meter is available for total multiphase measurement. In many cases a combination of two technologies, e.g., electrical resistance tomography along with electromagnetic flow meters, are deployed for three flow measurements. These are discussed in subsequent sections.

1.3.2 MULTIPHASE FLOW COMPUTATIONAL REQUIREMENTS

Multiphase flow consists of the three phases: hydrocarbon/oil, gas, and water. Therefore, for getting the individual volumetric flow rate of these phases, the fractions and velocities of each of the phases have to be found meaning total

six (at least five) measurements are necessary. We first concentrate on Eq. IX/1.3.0-1.

Volume flow:

$$q_i = \alpha_i \cdot v_i \quad \text{(IX/1.3.0-1)}$$

where α_i and v_i, respectively, are the phase fraction and velocity of each phase/component. Here it is to be noted that Eq. IX/1.3.0-1 has been shown as the flow rate, in the sense that it has been assumed that other conditions, like area, etc., would be constant.

So, if we multiply q_i with the associated density ρ_i we get the mass flow rate:

$$q_{mi} = q_i \cdot \rho_i. \quad \text{(IX/1.3.0-2)}$$

It is general practice to get the density of the oil, water, and gas through thermodynamic calculations using pressure, temperature, and volume data, i.e., PVT data. As indicated in Chapter I, Section 3.4.2 one needs to get five pieces of data, i.e., from three individual velocities, and two-phase fraction (as third-phase fraction can be obtained by subtracting the sum of two know phase fraction from unity). The phase volume flow rates of oil (hydrocarbon), gas, and water are found by combining the fractional measurement and velocity measurement. Mass flow rates can be obtained by multiplying the individual volume rate with the corresponding density from PVT data. We now examine the cases shown in Fig. I/3.4.2-1.

1. **Full separation:** Gas is separated, so any standard gas flow meter, e.g., Venturi, turbine, etc., can be used to measure the gas volume flow; if the density at the operating condition is known then mass flow of gas flow can be obtained. The down side to the separator is the liquid flow, so if any liquid meter, e.g., a PD meter, is used to measure the total liquid flow (duly corrected). If WLR is found by, e.g., a water cut meter (microwave), one can compute the volume flow of water and hydrocarbon/oil.
2. **Part separation:** Here a wet gas meter has been used to measure the gas volume rate. A simple Venturi meter, as discussed in connection with the wet gas meter in Section 1.2.5 (of this chapter), or DP ratio method can be used to measure the velocity of gas duly corrected on account of the presence of liquid in gas. Normal, Venturi calculation as per ISO 5167:2003 (described in Chapter II) cannot be applied directly. Since separation is done from the bottom it is a liquid with low GVF, hence a standard two-phase liquid multiphase metering can be applied to measure liquid flows.
3. **Sampling method:** This is already described in subsection 3.4.2.3 of Chapter I and so not repeated here. GLR is basically a multiphase meter to give the output for total flow and the gas−liquid ratio. Thus it is possible to get the gas volume flow and total liquid flow. Now with WLR, one gets water in liquid, hence this, in conjunction with total liquid flow, gives the flow rates of water and oil. All such flow rates are volume flow rate, and mass flow can be obtained using the density factor from PVT data.

1.3.3 MULTIPHASE METER IN OIL AND GAS

There have been applications of multiphase flow measurement requirements in many plants. However in the oil and gas area (especially in oil exploration/custody transfer), real multiphase flow measurement applications are major issues and multiphase flow comprising even four phases are possible. In oil and gas well testing and production management is a big issue requiring multiphase flow measurement applications. Apart from production allocation metering, custody transfer/fiscal measurements and subsea applications also require multiphase flow metering. For fiscal measurement guidelines are available from Ref. [1] and ISO/PRF TR 11583:011. Therefore, short discussions on the same will be covered in this part. Well monitoring and well testing are two major application areas discussed in the following subsections.

However, it is better to have a look at the pros and cons of MPFM with respect to conventional systems of test separators. For this Table IX/1.3.3-1 may be referenced.

TABLE IX/1.3.3-1 Pros and Cons for MPFM vis-a-vis Test Separator

Pros	Cons
Continuous operation possible and time-saving	MPFMs are complex systems that requiring prior knowledge for proper operation of the same
Installation and operating costs are much lower than conventional system	MPFMs may cause instability over time
Test separator, test lines, manifolds, and valve systems as well as different single-phase meters are eliminated	MPFMs are very sensitive to physical properties of the phase; hence slight variation may cause errors in reading
On account of continuous operation, total uncertainty will be lower than that for conventional system	Periodic variation is an absolute necessary
Overall cost saving and space saving	In absence of any standard for multiphase fluid sampling, it is difficult to operate

1.3.4 WELL MONITORING

In this section various ways and means for well monitoring and use of MPFM in such monitoring are discussed.

1. **Basic monitoring:** Even if there is increased uncertainty associated with instantaneous phase flow rates, monitoring data with MPFM will have better resolution than that with random well testing with a test separator. This is because the changes in performance between tests are not recorded when using separators. Thus the total uncertainty in well data using MPFM will be reduced. Also, such data are always valuable resources. Such data will be helpful in installing a new MPFM which saves space, weight, and cost when compared with the installation of a new test separator. During instability of a well it is necessary that there is some degree of control on the same so that it can be connected to the production line. With a conventional separator it is not possible to get details of variations in the flow rate. In such situations MPFMs become useful tools. A typical use of MPFM in well monitoring has been depicted in Fig. IX/1.3.0-1. As stated earlier, MPFMs are useful for subsea installations for monitoring of flow rate from wells/long flow lines. It is important to note that retrieval of an MPFM for maintenance or repair may be expensive, difficult, or impossible. In situ calibration is normally not available. Therefore, the reliability and stability of subsea meters is of paramount importance and needs to be addressed by the manufacturer of the MPFM, the subsea system integrator, and the operator [1].
2. **Production optimization:** Gas injection and production optimization basics have been illustrated in Fig. IX/1.3.0-2. As is clear from this figure, it is possible to control the production rate for which it is necessary to get the production readings. In many places now MPFMs are used to optimize the gas lift injection rate as they are capable of instantaneously showing the oil flow rate as a function of the injection gas flow rate. This saves time normally required by test separators to generate the same information. However, while selecting MPFMs for this purpose, one issue that should be kept in mind is that most gas lift operations are relatively high GVF applications, so the MPFMs should be capable of handling this high GVF operation, otherwise a wet gas meter could be used.
3. **Flow assurance:** According to the Handbook of Multiphase Flow Metering (standard handbook [1]) "*Flow assurance includes all*

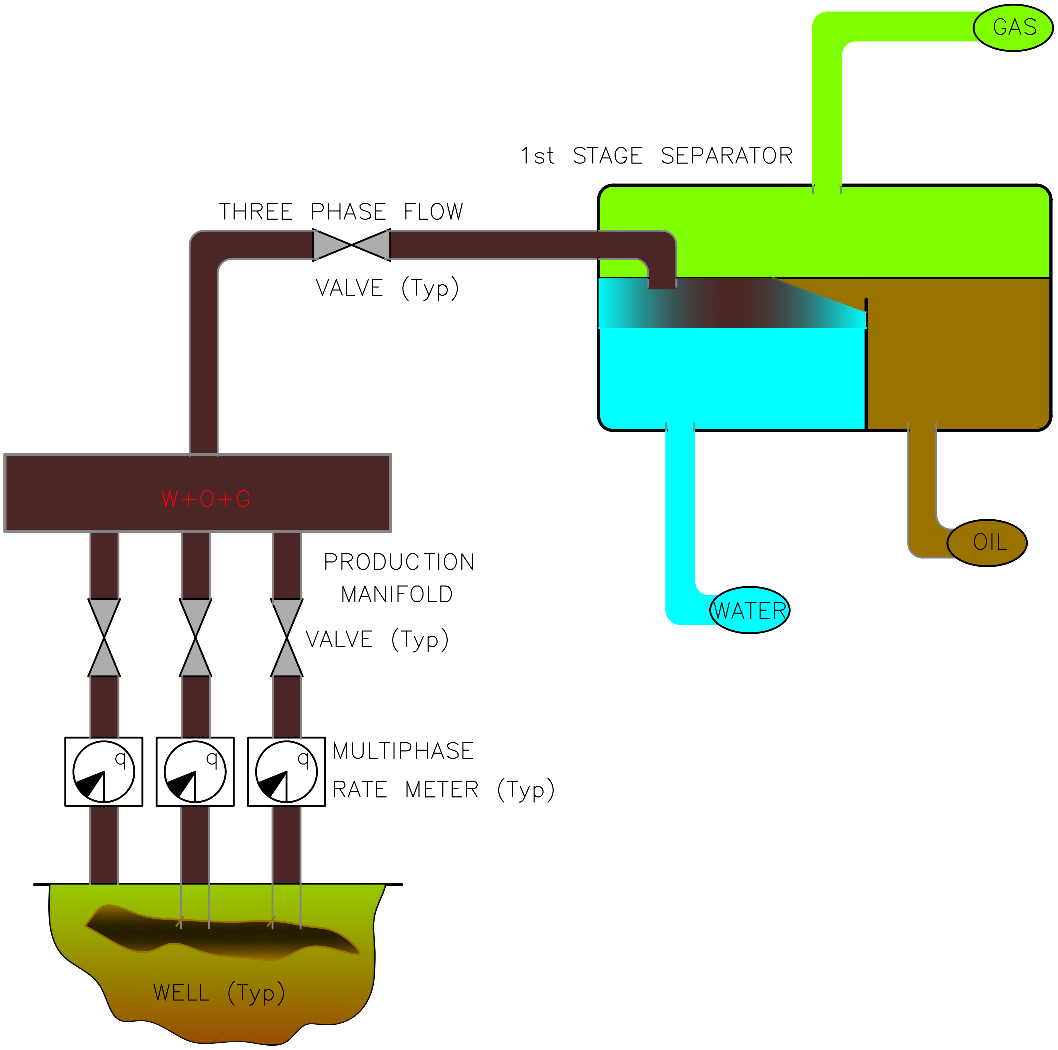


FIGURE IX/1.3.0-1 Well monitoring by MPFM.

Gas lift: It is an artificial but effective method for lifting well fluid. Here high-pressure gas is injected into the tubing at a maximum possible depth which is determined by well depth and pressure of injected gas. This gas reduces the density of the mixture and the bubbles have a scrubbing action on liquid. On account of pressure differential, fluid flows into the well bore.

Production Optimization: Basically it stands to represent production control where it is possible to set a target for production of gas and oil perhaps water i.e. to maximize gas and/or oil production and minimize water or to run oil production and gas oil ratio (GOR) to maintain energy of reservoir.

FIGURE IX/1.3.0-2 Gas lift and production optimization.

aspects that are relevant to guarantee the flow of oil and gas from reservoir to the sales or custody transfer point. It often involves facility engineers, production technologists and operations staff, and they evaluate and study the hydraulic, chemical and thermal behavior of multiphase fluids." So, with the use of MPFMs it may be possible to identify potential blockages due, e.g., to hydrates, etc., as described earlier. In such cases trending is important and naturally repeatability is more important than absolute accuracy. For fiscal measurements, according to the Norwegian petroleum directorate, a few standards like the latest versions of API MPMS RP 86, API MPMS Publ 2566, and ISO/PRF TR 11583 should be followed. Here major references are given for north sea explorations (author worked for), however other international standards are equally applicable.

1.3.5 WELL TESTING

In this section a short description and discussions are presented on well testing, where there are a number of requirements for MPFMs.

1. **Well testing basics:** Based on the results of well testing, many major decisions, such as new well(s) drilling, shutting down of wells, reduced production from the reservoir, etc. are taken in large fields, e.g. the North Sea. Conventional ways were (are) use of test separator. Test separators have some limitations and major issues related to this include the following:
   - *Sizing:* When undersized, separators will have less residence time, causing bad quality of separation. With poorer separation there will be carry over, i.e., liquid carry over in the gas stream and/or gas carry over in the liquid stream;
   - *Microbubbles:* For very viscous liquid, there may be formation of microbubbles, which are difficult to separate;
   - *Emulsion:* Foams and emulsions formed are difficult to separate;
   - *Maintenance and calibration:* Poor maintenance and calibration of reference flow meters and secondary instrumentation [18].

   Replacement of the test separator by an MPFM can be effective under the following conditions:
   - *Decision:* Firm decision not to utilize; it is decided to not install a test separator in the processing plant;
   - *Capacity increase:* When there is a need for a capacity increase of well testing;
   - *Other use:* Test separator left for other uses.

   Now it is time to understand the well testing methods:
2. **Conventional well testing with a test separator:** Conventional well testing is usually performed by means of a separator dedicated for well testing purposes. Flow of well streams is measured by separating streams (i.e., high vapor-pressure oil, gas, and water) by the test separator as shown in Fig. IX/1.3.0-3. Test separators are normally developed with suitable instrumentation with an estimated uncertainty better than 2% and 1% for the gas and liquid phases, respectively. During well testing, parameters like choke opening, wellhead flow pressure, and separator pressure and temperature are monitored and recorded. Also during testing, fluid samples are normally taken. Each well may be tested at one or more settings of the well's choke and all such measurements are recorded. All this information is important until the next well test is carried out. For wells where daily control is needed, for example, to keep wells stable or to produce at optimum flow rates in order to utilize the full capacity of the production facilities, this conventional system may not be satisfactory [1].
3. **MPFMs for well testing:** The purpose of the test separator is to separate the phases so that single-phase flow meters can be used. In this method, MPFMs are for measurement purpose, hence the need for a test separator is not there. However, when a MPFM is installed in addition to an existing test separator, there will be more flexibility, providing options for the test separator and the MPFM for well testing, thus the overall testing capacity is increased.

   Also, one can use only the MPFM for well testing and hence use the test separator as a normal production separator and thereby

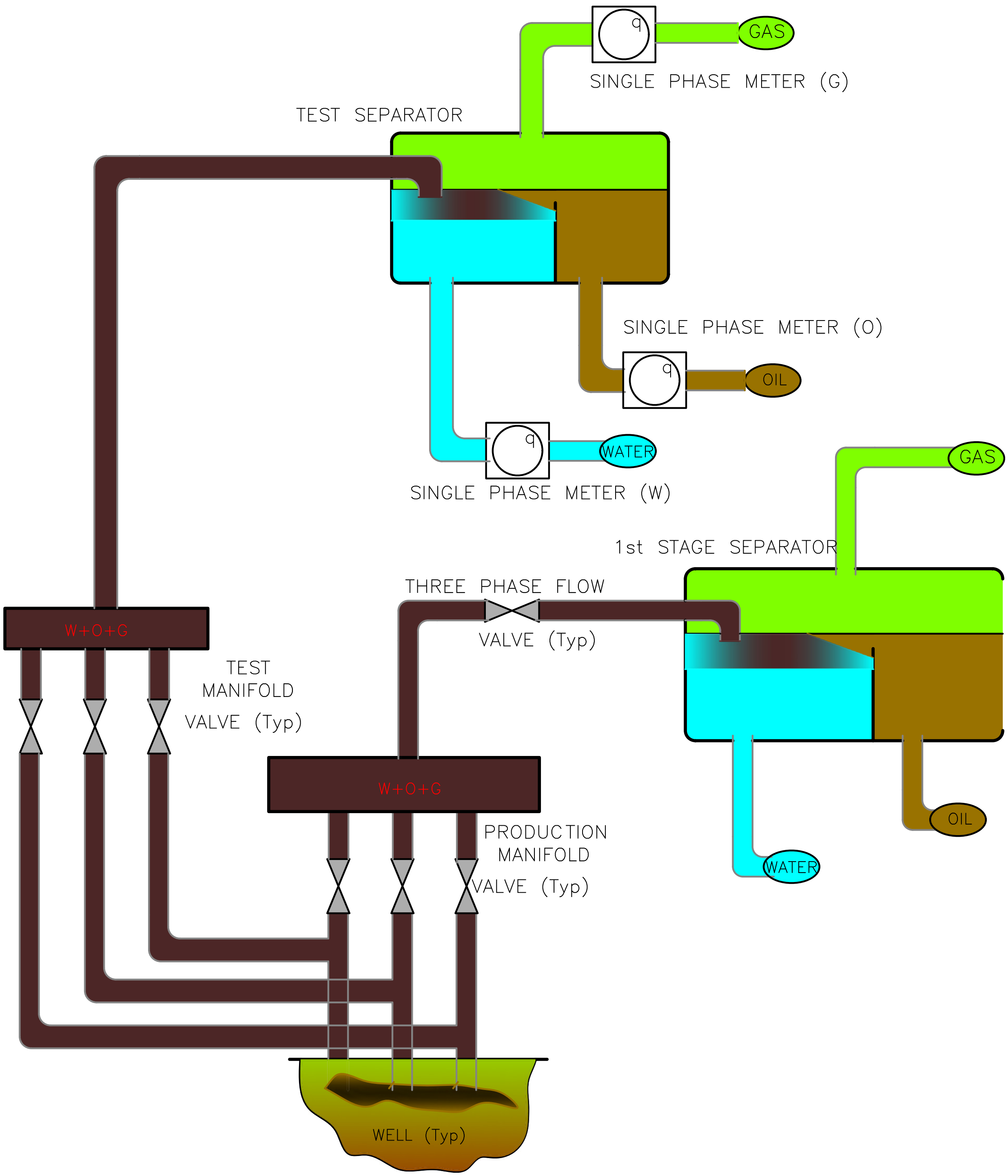


FIGURE IX/1.3.0-3 Conventional well testing.

increase the total production capacity of the processing facility, as shown in Fig. IX/1.3.0-4A. Major advantages come from the time saving (required for separator filling up the stabilization of the separator). It is possible to completely replace the test separator with an MPFM, as shown Fig. IX/1.3.0-4B. In such a case there will be savings of space and cost, in addition to the cost savings referred to above. This may be a solution for fields in the decline phase, where production from the well does not match the size of the test separator any more [1].

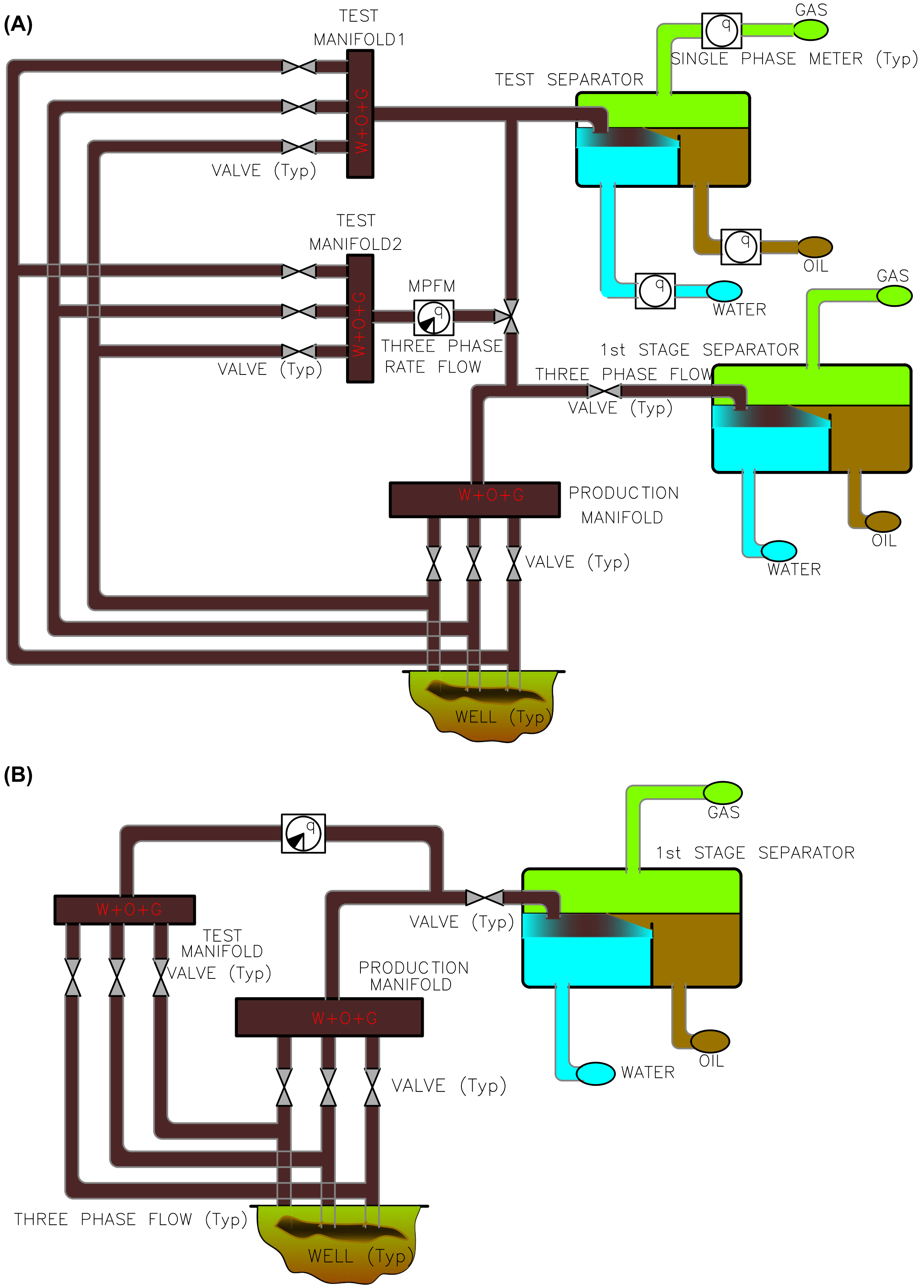


FIGURE IX/1.3.0-4 Well testing and MPFM. (A) Increased well testing capacity with MPFM. (B) MPFM to replace test separator.

1.3.6 PRODUCTION ALLOCATION METERING

For production allocation measurements, the requirements are stronger than those for well testing (especially in terms of uncertainty, calibration etc.). Unmanned wellhead platforms have MPFMs on each individual well for monitoring and surveillance and the main tie-in stream can be measured by an MPFM, which is frequently "proved" to provide k-factors by a test separator equipped with measurement equipment to a fiscal standard [1]. MPFMs have a long proving period. When the test separator is not used as a "prover" it can be used for other purposes [1].

1.3.7 FISCAL OR CUSTODY TRANSFER MEASUREMENT

For different production licenses with a common processing facility or flow line, it is necessary to meter the production from each license area separately before it enters the common facility. The metering of the production from each license area is normally the basis for allocation of each field licensee's ownership to the well streams at the common processing facility. Fiscal or custody transfer measurements are the basis for money transfer, naturally this measurement is very important. Normally these are governed by national government directives, e.g., standards relating to measurement of petroleum issued by the Norwegian Petroleum Directorate (NPD). Also for chemical injection (methanol, demulsifier), gas lift optimization and for other optimum production issues also MPFMs are deployed.

2.0.0 MULTIPHASE FLOW MEASUREMENT ESTIMATION AND TYPES

Now we go into the instrumentation details related to multiphase flow measurement. In this section we intend to cover the measurement of velocity and phase fractions that we discussed earlier, along with their pros and cons as an introduction to various measurement technology. Also in this section are discussions on wet gas meters and water cut meters. The discussions start with measurements of phase flow and phase fraction.

2.1.0 Phase Flow and Phase Fraction Measurement

In-line multiphase flow metering is normally done by measurement of the phase fraction and phase velocity/flow. Depending on the case phase velocity, volume flow (PD meters) and mass flow (Coriolis mass flow meter) are measured. Also, it is necessary to measure the phase fraction. The following are major measurement and instrumentation technologies deployed. deployed for in-line (without any separator) multiphase flow measurements:

1. Microwave technology;
2. Electrical tomography
   - Capacitance
   - Conductance;
3. Gamma ray densitometry or spectroscopy;
4. Neutron interrogation;
5. Wire mesh;
6. Needle probe;
7. PIV;
8. LDA;
9. Differential pressure using Venturi, V-cone, or other restriction;
10. Positive displacement;
11. Ultrasonic;
12. Coriolis mass flow meter;
13. Cross-correlation of electromagnetic, radioactive, ultrasound signals (to calculate flow velocities);
14. Magnetic resonance technique;
15. VEGA isokinetic sampling (VIS).

In most cases two or more of the above devices are used. However, there are single instrument types also e.g. magnetic resonance and VIS mentioned above. However these are somewhat proprietary in nature. Some interesting things to be noted here are: Venturi and V cone are DP elements that can be used to measure phase velocity. While phase fraction can also be measured by DP method as discussed in

Subsection 1.2.3.2 and in that case the DP element is not required. While the majority of conventional single-phase flow measuring devices such as, US and Venturi are used for measuring phase velocity, some can directly measure flow, such as PD meters. The Coriolis meter can be used for mass flow/density measurement of phase with limitations already discussed earlier in subsection 1.2.4.1. There are a few other types of measurements, such as wet gas metering and water cut metering. Brief discussions of such metering systems have been covered in Sections 1.2.5 and 1.2.6, respectively. The wet gas meter is basically meant to measure gas flow with due corrections for liquid carry over. Water cut basically measures WLR—a kind of phase fraction. Since in most cases these are associated with some sort of separation, they cannot be considered as in-line meters in true sense. Based on the discussions on metering principles discussed earlier, wet gas meters and water cut meters have been covered in this section. A virtual metering system is another new area for multiphase flow measurement. This is discussed in Section 2.4.0 of this chapter. Other in-line instrument technologies have been covered in the next section. From there it can be concluded, depending on the actual requirement necessary, that a combination and selection of technology is used. We now briefly discuss phase flow/velocity measurement.

2.1.1 PHASE FLOW OR VELOCITY MEASUREMENT

1. **DP element:** Venturi/V cone meters, and at times orifice plates, are used to measure phase velocity. In these DP elements, as the name suggests, differential pressure across the upstream section and the throat section or downstream of the device is measured and can be related to the flow rate based on the change in velocity due to restriction. These are discussed at length in Chapter II. While Venturi/orifice measurement technology for single-phase flow is guided by ISO 5167:2003, the V cone is basically a proprietary item and hence is not covered by ISO. In this connection rereading of Chapter II is recommended. However, direct application of equations from ISO 5167:2003 is not permitted on account of the necessity for a few corrections. The corrections necessary for DP element as wet meters have been outlined in Section 1.2.5. However, most manufacturers apply their own corrections or compensations to the standard Venturi or other DP equations.
2. **Positive displacement (PD) flow meters:** PD flow meters measure the volumetric phase flow rate of a liquid or gas by separating the flow stream into known volumes and counting them over time, as already discussed in Chapter IV. It could be a part of MPFM to measure total volumetric multiphase flow rate and phase flow.
3. **Other velocity-sensing instruments:** There are some other velocity measuring instruments, such as the turbine flow meter, vortex meter, and electromagnetic flow meter that are often used to measure phase velocity, depending on their applicability for the particular purpose, e.g., the electromagnetic flow meter can be used only for a phase with suitable conductivity. Vortex is better suited for gas phase. All these instruments have been discussed in Chapter V.
4. **Cross-correlation:** Velocity measurement by cross-correlation is a standard method in phase velocity measurement. As indicated in Chapter I, some properties of the flow are measured by two identical sensors at two different locations, separated by a known distance. As the flow passes the two sensors, the signal pattern measured by the first sensor will be measured by both sensors, and only the second sensor will measure the signal after a short period of time (dt) corresponding to the time it takes the flow to travel from the first to the second sensor. The principles of operation have been elaborated on in detail in Section 8.3.0 of Chapter I, hence this may be referenced. For flow and velocity measurements, microwaves, gamma rays, DP elements, and electrical impedance principles are commonly used in this method.

2.1.2 PHASE FRACTION MEASUREMENT

There are a number of ways that phase fraction can be measured. In this subsection this has been elaborated on. In this connection, the discussion in Section 1.2.3 of this chapter may be referenced. In Section 1.2.3 the discussions were on void fraction measurement for two-phase flow of gas and liquid. This is basically a part of phase fraction which may also include measurement of phase fractions of water, etc. Gamma ray principles with high energy source, used in finding the void fraction, were easy because there is a good gap in the absorption of energy in gas media and liquid media. However, the same principles can be extended to measure *any* phase fraction. We start the discussions with gamma rays.

1. **DP method:** In this method, the energy equation normally used in ISO-5167:2003, for calculating flow, can be utilized for phase fraction measurement. The DP method for finding the phase fraction is discussed in Subsection 1.2.3.2, where detailed discussions on the same have been presented; the above is also applicable for multiphase phase fraction measurements also.
2. **Gamma ray:** When discussions in Section 1.2.3 are recalled it is noted that in principle a gamma ray attenuation measurement is applicable to all possible combinations of two- and three-phase flows, only in the later case will there be a requirement for at least two sources. There are few measurement limitations and the measurement works in the whole range from 0% to 100% water cut and 0% to 100% GVF applications [1]. There are two main types of gamma ray attenuation used in multiphase flow meters. A single high-energy narrow-beam gamma ray emitted by a nuclear source or X-rays are mainly meant to distinguish the gas from the liquid, as shown in Fig. IX/2.1.0-1B.

   Other is dual energy, also referred to as dual-energy gamma ray attenuation (DEGRA). DEGRA uses both high- and low-energy gamma rays emitted to firstly distinguish the gas from the liquid, and then the oil from the water. A low-energy absorption pattern has been depicted in Fig. IX/2.1.0-1C. Therefore, with dual sources it is possible to find all phase fractions in three-phase flow. As shown in Fig. IX/2.1.0-1A, the same amount of radiation is sent through gas/oil/water. In the case of high energy there is a clear difference in the absorption between gases and liquids. In the case of high-energy radiation, absorption by gas is much lower than that by oil or water, hence at the detector there is a high count. On the other hand, counts detected for oil and water are low due to higher absorption. It is also found that with high-energy radiation, absorption patterns for oil and water are very similar and close to each other. Because of this the plot of the count, as shown in Fig. IX/2.1.0-1B, marks the difference between liquids and gas. Another interesting fact that has been depicted in Fig. IX/2.1.0-1B, is that when mixture flow is plotted there will be a minimum—maximum point in the plot to signify the slug flow pattern, and bubble (mist) due to variations in the presence of gas in the liquid, i.e., to show where the mixture is liquid-dominant and where it is gas-dominant. When the same thing is done with low energy, it can be seen that absorption by gas is the same as in the previous case, but there is some difference in absorption patterns in oil and water, which absorbs the highest amount. This creates a difference in absorption patterns between oil and water, as clearly shown in Fig. IX/2.1.0-1C. In the case of DEGRA both high and low energies are utilized. When radiation absorption count is carried out with high-energy radiation versus low-energy radiation one gets a curve as shown in Fig. IX/2.1.0-1D. As shown in the figure each of the corner points indicates the pure state of the phase, while points inside indicate the probable combination

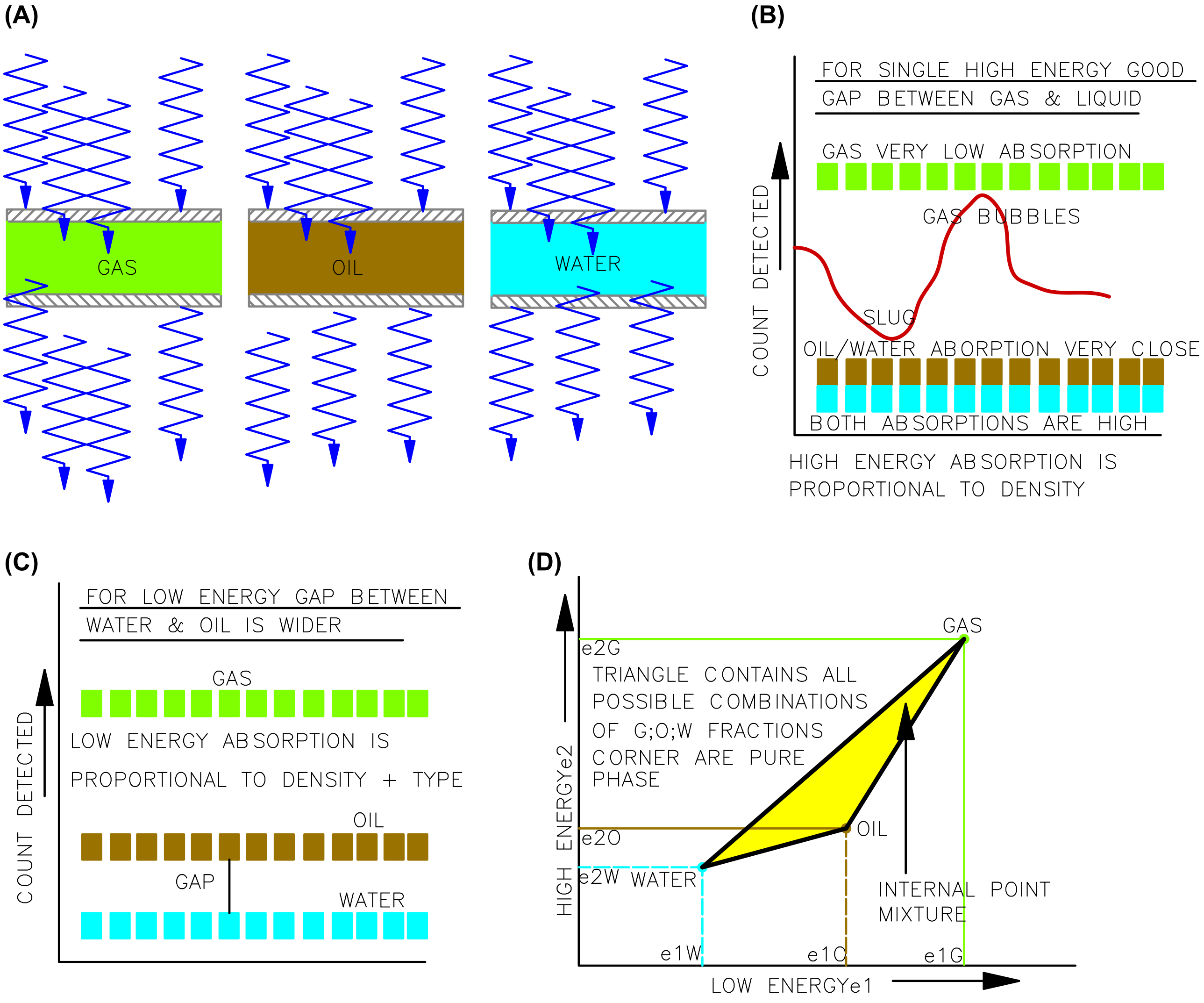


FIGURE IX/2.1.0-1 Gamma ray and phase fraction. (A) Gamma energy absorption. (B) High-energy absorption types. (C) Low-energy absorption types. (D) Possible phase fractions.

of the three phases depending on their position. The shape of the triangle is guided by the energy levels used, i.e., radioactive source used, pipe diameter (for z in Eq. IX/1.2.3-16), and detector characteristics. However, fluid properties may also influence the triangular shape, i.e., if the energy levels are too close the triangle will transform into a line and obviously cannot be used for a three-phase composition measurement [1]. This is a descriptive part, we now concentrate on the computational part as defined in Section 1.2.3.

Eq. IX/1.2.3-16 gives us $I = I_0\ e^{-\mu z}$. In the case that it is applied to a mixture comprising water, oil, and gas one can write $I_w = I_0\ e^{-\alpha w \mu z}$, where α_w stands represents the phase fraction of water and the same for gas and oil would be $I_w = I_0\ e^{-\alpha g \mu z}$ and $I_w = I_0\ e^{-\alpha o \mu z}$, respectively, where α_g and α_o indicate the phase fractions for gas and oil, respectively. The attenuation coefficients (μ_i) are found through calibration. From the above discussions it is clear that using DEGRA we have two sources necessary to get the three-phase fraction (refer to the discussion in Subsection 1.2.3.4). The two phases can be obtained using Eq. IX/1.2.3-18 or Eq. IX/1.2.3-19, as applicable.

So, referring to Fig. IX/1.2.3-4C, one can write in a generalized way

$$I_A = I_{0A} \cdot e^{-(\mu_1 A\alpha_1 x_1 + \mu_2 A\alpha_2 x_2 + \mu_3 A\alpha_3 x_3)} \quad \text{(IX/2.1.0-1)}$$

$$I_B = I_{0B} \cdot e^{-(\mu_1 B\alpha_1 x_1 + \mu_2 B\alpha_2 x_2 + \mu_3 B\alpha_3 x_3)} \quad \text{(IX/2.1.0-2)}$$

$$x_1 + x_2 + x_3 = H \quad \text{(IX/2.1.0-3)}$$

Taking the log on both sides it is possible to get linear equations.

3. **Electrical impedance tomography:** Electrical impedance tomography (EIT) is of two types: conductivity and capacitance, as already discussed in Subsection 1.2.3.3.
4. **Microwave:** This type of measurement has a lot of similarity with the capacitance type but is different. There are different types such as the following:
   - *Resonator sensor:* The resonant frequency changes with the permittivity (ε) of the medium. If f_0 is the resonant frequency of the sensor filled with air, and f_r is the measured resonant frequency when the sensor is filled with the fluid, then the permittivity is related to the resonant frequency by:

     $$\varepsilon = \left(\frac{f_0}{f_r}\right)^2 \quad \text{(IX/2.1.0-4)}$$

     Equation may be compared with deduced frequency in Eq. IX/3.2.3-2. As a microwave is also an electromagnetic wave, the relation of absorption expressed in Eq. IX/2.1.0-1 or Eq. IX/2.1.0-2 can be applied here. Hence, in a generalized way it can be:

     $$I = I_0 \cdot e^{-(\mu_1 \alpha_1 x_1 + \mu_2 \alpha_2 x_2 + \mu_3 \alpha_3 x_3)} \quad \text{(IX/2.1.0-5)}$$

     From here it transpires that the relation is independent of the shape of the individual resonator, and therefore needs no calibration other than the measurement of f_0. It is the measurement of frequency. As f_0 only depends on the physical size and shape of the resonator, the resonator measurement method is accurate. However, there is a limitation to the measurement type, as it can be used only with low-loss media, such as oil continuous and water continuous fluids that absorb the microwave energy too fast for resonance to happen.
   - *Variable frequency:* Here the measurement is carried on a varying frequency. The attenuation in water-continuous fluids is high at high frequencies, so this concept can be utilized to change the measurement frequency with the permittivity of the fluid. Thus it can be used for measurement of the change of phase, such that the meter detects the frequency, where the change of phase is constant, i.e., *the frequency*, where the change of phase is equal to a fixed value [1].
   - *Fixed frequency:* This system consists of one transmitter and one receiver, both operating on the same particular frequency. Transmission and reception of signals are through the medium, so extreme caution should be undertaken to avoid any reflection from the pipe, hence if necessary a suitable waveguide can be used. On passing through the medium there will be distortion, which can be attenuation or phase change detected by the receiver.

A practical microwave MPFM uses the resonator principle for oil-continuous fluids, and the varying frequency transmission principle in water-continuous fluids, utilizing the same probes [1].

Details on microwave type measurements have been elaborated in Sections 2.3.0 (water cut meter) and 3.2.0 (multiphase flow metering). With this the discussions on phase fraction measurement are concluded and we now look into the details of wet gas meters in the next section.

2.2.0 Wet Gas Meters

(Metering issues, including various corrections and ISO TR 11583 correlations have been presented in Section 1.2.5, so this section may be read in conjunction with Section 1.2.5.)

Liquid and gas flowing together in a pipeline cover a huge spectrum of flow conditions. For natural gas production, all combinations of gas, oil (hydrocarbon), and water flows can be

found. To date, wet gas flow is not quantitatively defined by any codes and standards body [19]. There are several interpretation of wet gas, one with GVF has been referenced in Section 1.2.5, some also are related to the Lockhart-Martinelli number/parameter X or X_{LM}. Some consider 0.3 as wet gas. On the basis of this there are three types [20]:

- Type I, when $X_{LM} \leq 0.02$; typical metering by: DP elements, turbine, ultrasonic, vortex, and Coriolis (highest over-reading).
- Type II, when $0.02 \leq X_{LM} \leq 0.3$; typical metering by: dual DP, dual Venturi and Vortex, Venturi with tracer element.
- Type III when $X_{LM} > 0.3$; multiphase meters.

The way that a liquid phase is dispersed in a gas pipe flow is referred to as *flow pattern*, and it has a direct impact on wet gas flow. The discussion on *flow pattern* for both horizontal and vertical pipes has been covered in Subsections 1.1.3.4 and 1.1.3.5. In oil and gas industries wet gas has extensive use, some of which are as follows:

- Reservoir monitoring;
- Contractual allocation;
- Production optimization and flow assurance;
- Fiscal monitor and custody transfer;
- Water breakthrough knowledge (investigation for a sudden increase in liquid content in gas).

Meters are available as three-phase meters or DP meters with other sensor(s). As such, the governing standards are ISO DTR12748:2014 and ISO TR 11583:2012 [21].

2.2.1 DP METHOD (DP ELEMENTS: VENTURI, V CONE, ORIFICE)

It has been found that DP meters, to be more specific, Venturi meters, have shown the most stable and repeatable wet gas performance than others. The other traditional gas meter designs cannot maintain stable performance, i.e., varying performances and limited use with wet gas flows. However, it is worth noting that from a study of the literature, it can be said that other DP elements like orifice plates and V cones also find their applications in wet gas flow and have been found to have less over-reading, but are not as popular as Venturi.

1. **Venturi tube:** The majority of commercial wet gas (also multiphase) meters incorporate a Venturi tube, along with other measurement technology, to determine the flow rate of the individual phases including wet gas measurement. Venturi tubes are more suited because they are simple, robust, and cost-effective flow meters. Also, from the discussions in Chapter II, it is clear that the accuracy of Venturi, as well as pressure loss in Venturi, are much better than many other DP elements. DP metering is straight forward and providing various corrections and gas correlations are easy. Also from Section 1.2.5 it could be noted that DP meters are significantly affected by the presence of liquid in the gas flow. All such corrections and correlations have been presented in Section 1.2.5, so that wet gas can be measured well by DP meters. According to the suggestion of De Leeuw (1997) in his research one gets that *the permanent pressure loss across the Venturi meter was affected by the liquid presence in the gas flow. Therefore, reading the upstream to throat DP and also the upstream to downstream DP could potentially give enough information to predict both phase flow rates without any requirement for an independent liquid flow rate estimation*. This is a single Venturi wet gas flow measurement concept and his arguments were in favor of "pressure loss ratio," i.e., DP read by the Venturi meter (ΔP), is different between dry and wet gas flows [22]. In this connection, Subsection 1.2.5.5 may be referenced. According to him "The potential for the pressure loss measurement is to use it as a means to determine the liquid content of the flow, from which the over-reading factor can be determined accordingly. In essence this would form a simple two-phase flow meter…" It is possible to develop a single element utilizing a V cone wet gas meter, as described in detail in Ref. [22]. We now look into the details of another DP element V cone.

2. **V cone:** The V cone is designed with a centrally located restriction leaving an annular opening around the cone. This is in contrast to other DP elements. Therefore, wet gas can pass freely along the pipe wall without touching the central V cone. Hence it is better suited for wet gas applications. From a study of the literature it was found that for low-pressure wet gas, a very small amount of liquid is held before and after the cone, which was a main consideration against the orifice plate (discussed next). This indicates that the device is well suited for measurement of wet gas for some applications. However, the discharge coefficient, C_d, of the V cone decreases with an increase in the liquid loading in wet gas. Such a fall in C_d depends on the beta ratio and line pressure. It is therefore recommended by the manufacturer to use a beta ratio less than 0.59. A flow metering accuracy of 1% AR can be achieved in a V cone element.
3. **Orifice plate:** Initially it was thought that the orifice plate could potentially act as a dam, which would not be good as a wet gas meters [23]. However, on analysis of data from orifice plates over a few years it has been suggested that no such problem has been found. In 2011, CEESI placed an orifice plate in the middle of a view port and recorded various horizontal wet gas flow conditions through the orifice plate. It was shown that no significant liquid hold up occurred at the plate, regardless of the flow pattern [23]. Also, it has been noted that *over-read* in an orifice is lower than that for a Venturi. Therefore, there is no reason to think that orifice plates cannot be used in wet gas measurement. In fact, earlier, Nguyen patented a design using an orifice plate in series with a Venturi for measurement of wet gas. However, it was found that liquid properties can affect the wet gas flow response of an orifice meter. Gas with water or gas with water and light hydrocarbon liquid wet gas flow can produce slightly different *over readings* than gas with hydrocarbon liquid flow only. Orifice plates may have some damaging effects when used in wet gas, hence it is essential that the same should be regularly checked, indicating that orifice plates are maintenance-prone.

   With this the discussions on DP elements for wet gas meter come to an end with the concluding facts that with an increase in Lockhart-Martinelli parameter the DP created by the primary element will over-read and such over-reading could be as high as 50%, also they tend to behave slightly differently. Therefore, it is suggested that the DP method is well suited for up to a certain X_{LM} value.
4. **DP transmitter:** Common differential producers, such as Venturi, orifice plates, and V-cones will "over-read" the true gas flow rate due to the presence of liquid in the fluid stream. The amount of over-reading is directly correlated to the amount of liquid. This means that the DP created by a wet gas flow through a DP element is *higher* than if the gas phase alone flowed through the meter. Therefore, DP transmitters should be selected accordingly to avoid exceeding a DP transmitter's range. It is better for wet gas flows with XLM ≤ 0.3 to size the DP transmitter range for DP elements. For details on DP transmitters (or multi variable transmitter—MVT) in Section 2.1.0 of Chapter XI may be referenced.

2.2.2 NON-DP WET GAS MEASUREMENTS

There are a number of non-DP instruments, which can be used to measure wet gas in place of DP elements. Major non-DP elements used for wet gas measurements are listed here:

- Turbine flow meter;
- Ultrasonic flow meter;
- Vortex meter;
- Coriolis mass flow meter.

Detailed descriptions and other details of these have been discussed in Chapter V, except the Coriolis mass flow meter, which is covered in Chapter VI. This indicates that like DPs, all other meters also measure velocity and the Coriolis measures mass/density for wet gas flow measurement. The pros and cons of these instruments have been enumerated below.

1. **Turbine meter:** Turbine meters are very good for velocity measurement in single phase. Even excellent gas turbine meters are not very suitable when exposed to wet natural gas flows. On account of the presence of liquid, there will be the possibility of the blades of a turbine meter being damaged due to impact with the liquid present. Also, there can be particulates present during wet natural gas production. These particulates can cause wear to the meter bearings. Also, the meter response is unpredictable. Therefore, the use of a turbine meter in wet natural gas production in continuous basis is not recommended or considered. However, they can be used for flow measurement after complete *separation*.
2. **Ultrasonic flow meter:** Ultrasonic meters, which are basically noninvasive and nonintrusive, otherwise give a good response to gas flow. However, when these meters are exposed to natural gases they show a different response. Normally US meters will always over-read the gas flow rate and the presence of the liquid can affect the proper functioning of the meter by blocking transducers, etc. However, the meter types have been found to be successful when the presence of liquid is *very* low. Void fraction and liquid film thickness at the reflected point of the ultrasonic wave are mainly responsible for the over-reading of ultrasonic flow meters. Based on the film thickness, a suitable correlation can be developed for gas phase flow measurements. Nowadays, US meters have been found to be smart, with diverse software capabilities and diagnostic to support required corrections and diagnostic capabilities, so some of them can be used for wet gas measurement with particular flow patterns of stratified flow in horizontally mounted meters and mist flow in any meter orientation. However in real-life normal operation, such flow patterns are not guaranteed. So, for lower X_{LM}, it can be used with suitable correction for over-reading.
3. **Vortex meter:** Vortex meters are sturdy gas meters with a high turndown. Like ultrasonic meters, vortex meters will always over-read the gas flow rate. However, the magnitude of the over-reading *variations* has been noted. Over-reading shows a linear relationship with the Lockhart-Martinelli parameter up to some **critical** value, beyond which it is erratic. However, with change of bluff body orientation this was eliminated in the actual test. Also, the presence of liquid at times affects the functioning of the meter.
4. **Coriolis meters:** The Coriolis mass flow meter is an excellent liquid meter, and has also been accepted as a gas meter. However, it can have unpredictable behavior in wet gas conditions. For further details Subsection 1.2.4.1 may be referenced.
5. **Sonar:** The sonar flow-measuring technique is often used in a wet gas flow measurement system. The sonar technique has been elaborated in Section 9.0.0 in Chapter V and may be referenced there. This noninvasive technique is used to measure the total flow so that by measuring GVF, the gas flow can be computed. This is further elaborated for wet gas measurement in Section 2.2.3.

Now we shall investigate a typical commercial wet gas flow meter.

2.2.3 WET GAS FLOW METER (COMBINATION)

From the discussions in the section above it is clear that when the total flow and GVF are measured it is possible to compute the gas flow. In commercially available wet gas measurement the same techniques are used. The instrument discussed here is based on a commercially available water gas meter from *Weatherford Instruments USA [24] (courtesy: Weatherford Instruments)*.

Operating principles: The wet gas meter consists of an extended-throat Venturi and a sonar flow meter. Water cut measurement, as discussed in Section 1.2.6, is also used optionally to compute the flow of components in liquid phases also. This combinational instrumentation system has a wide operating envelope and can offer good accuracy for dry and wet gas measurements and

offers a stable response under multiphase flow conditions. As discussed in Section 9.0.0 of Chapter V, the sonar flow-measuring system measures the convection of turbulent vortices using an array of dynamic strain sensors. It measures the total flow rate over an extremely wide range of Reynolds numbers. Sonar is capable of measuring flow even in the presence of liquid, with minimum over-reading. As already discussed both in Chapter II and in Section 1.2.5, the DP drop across Venturi tube flow can be utilized to measure flow. A Venturi flow meter has well-defined over-reading, which is a function of wetness or liquid content in the wet gas stream. DP measurement across the Venturi is carried out by means of a multivariable transmitter (MVT) so that PVT values are also inputted to the flow computer. Thus the combination of sonar and Venturi in the flow meter yields total gas and liquid flow rates in real time. A typical flow computation has been elaborated in Fig. IX/2.2.3-1.

As shown in this figure, sonar gives the total flow and output from MVT in conjunction with

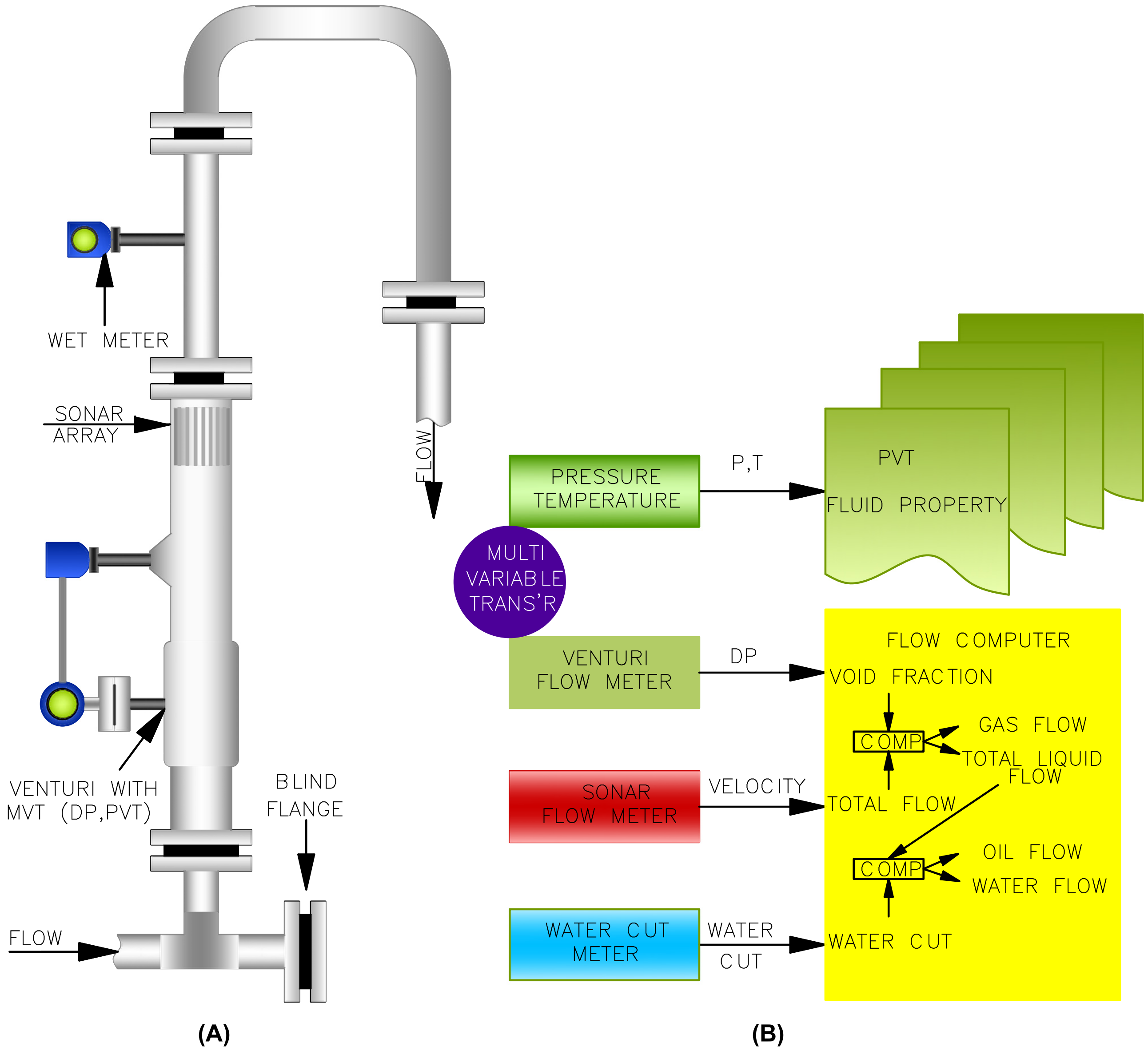


FIGURE IX/2.2.3-1 Wet gas meter. (A) Wet gas measurement. (B) Wet gas computation. *Developed based on the Weather Ford wet gas meter. Courtesy: Weather Ford USA.*

sonar data and can give gas flow, GVF, and total liquid flow. From this, the total liquid flow with the help of an optional **water-cut** (Section 2.3.0) meter, gas flow and water flow can be computed. Here multiphase water-cut measurement shown is an optional item for computation of water and oil flow from total liquid flow. Thus, this flow meter can be deployed as a true three-phase wet gas flow meter based on three independent primary instruments for the measurement of gas, oil/condensate, and water rates. Similar instruments are available from other manufacturers, e.g., Roxar Subsea Wet Gas Meters from Emerson.

Specification: A brief specification of this instrument has been elaborated as Table IX/2.2.3-1. It is worth noting that some features from other instruments have also been included in this specification. It is a generalized specification and may vary with any particular instrument.

In the following section water cut meters referred to above shall be discussed.

2.3.0 Water Cut Meter

Water cut is also known as on-line water determination (OWD) in API. From Table IX/1.1.1-1, we know that a water cut meter measures the water content in liquid. Of the various ways and means described in Section 1.2.6, change of dielectric/capacitance is the most popular. In this method, water cut is measured by exploiting the large difference between the dielectric constants of oil and water. However, there are variations in instruments in utilizing the type of electromagnetic waves used for measuring the permittivity difference. Different electromagnetic waves used include radio frequency (RF) and microwaves. There is another technique which uses near infrared radiation (NIR) absorption. This is an optical system, used for water cut detection. For water-in-oil emulsions (W/O) NIR finds more applications. For W/O, impedance spectroscopy is also used. Gamma rays can also be used. On account of simplicity, a change of capacitance,

TABLE IX/2.2.3-1 Specification for Wet Gas Meter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Operating range	90%–100% GVF		
2	Velocity range	5 to 40 m/s		
3	Operating temperature	Up to 150°C		
4	Material	Normally stainless steel 316		
5	Available pipe sizes	75 to 250 NB		
6	Connection flange	ANSI 600, 900, and 1500 lb		
7	Electronics	Mil grade suitable up to 60°C		
8	Communication interface	RS link MODBUS, CANBUS, Ethernet, Fieldbus may be possible also		
9	Power supply	240/110 VAC 50/60 Hz. Or 24 VDC		
10	Local display	Possible		
11	Uncertainty	GVF>98% 0.1% AR by vol.		
		GVF<98% 0.2% AR by vol.		
12	Sensitivity	2×10^{-4} abs vol.		
13	Hazard application	Yes, certificate from appropriate authority		
14	Optional	Water cut		

i.e., dielectrics, is more commonly used. With an increase in the amount of water in the flowing liquid stream, the net dielectrics of the fluid increases and, as a consequence, the capacitance increases.

On account of the difference in molecular structure between the two liquids, such dielectric development happens. Structurally, water has hydrogen atoms with an oxygen atom which has an affinity for the electrons of the two hydrogen atoms. This results in the electron density on the oxygen atom becoming greater. As a consequence, there is creation of a water molecule having a positively charged side and a negatively charged side. Because of this, water molecules will continuously try to align themselves when *faced* with an electromagnetic wave and there will be a difference in permittivity. The permittivities of water and oil (hydrocarbon) differ appreciably. Typically the variations of permittivity of water (ranging between 70 and 80) to permittivity of oil/hydrocarbon (ranging 2−2.3) is wide.

2.3.1 WATER CUT METER WORKING PRINCIPLES

There are broadly three types of water meter commonly used. EIT/magnetic resonance type can be utilized for measuring the water cut. These will be discussed later. Here, the working principles covered are RF type, microwave resonance type, and NIR type. These are described here:

1. **RF type measurement:** A water-cut meter uses RF electromagnetic signals to measure the permittivity of any oil/water mixture. The water cut is calculated by comparing the mixture permittivity with the *dry* oil and water permittivities. In this method a radio frequency signal (voltage) is transmitted through the sensing element, and the capacitance between the probe and the surrounding pipe is measured to interpret the water in liquid stream. The more water there is in the intervening fluid, the higher its capacitance. A change of capacitance with water cut has been shown in Fig. IX/2.3.0-1A. From the measured capacitance, the percentage of water in oil can be calculated based on a predictable relationship in the properties of the materials. The dielectric constant of water varies little with temperature, usually system electronics can compensate for temperature-dependent changes in the oil-phase dielectric constant [25]. There is a serious limitation of the systems. When the water content in an oil-continuous mixture increases, there will be an inversion point after which the “oil is dispersed in water” will become the “water dispersed in oil.” Naturally, at this point, the fluid becomes conductive, hence the capacitor is effectively “shorted out” and the measurement system will not function. This point occurs normally at around 0%−50% water with *light* oil, and 0%−80% with *heavy* oil. A silver lining in this is that most oilfields do not operate on the water-continuous side of the spectrum. These probes are available as insertion type probe. AMETEK is one supplier of this type of instrument.
2. **Microwave resonance technique:** From the above discussion it is clear that there will be a tendency for water molecules to align themselves. In this technique microwaves are used as an electromagnetic wave. On account of the higher permittivity of water, the propagation of microwaves will be *slowed* down. However, as hydrocarbon molecules have a much more symmetrical structure, they offer an insignificant resistance to the propagation of microwaves. This distinct difference in dielectric properties between water and oil has been exploited in measurement with microwaves also. Variations of permittivity with water cut are shown in Fig. IX/2.3.0-1B. Microwave resonance technology (refer to Subsection 2.1.2.4) allows an energy peak to occur at a defined frequency dependent on the sensor unaffected by the temperature of the electronics, aging, and calibration, etc. From the above discussions, it is clear that with an increase in water cut, the propagation of the microwaves is more and more counteracted, resulting in a corresponding decrease in

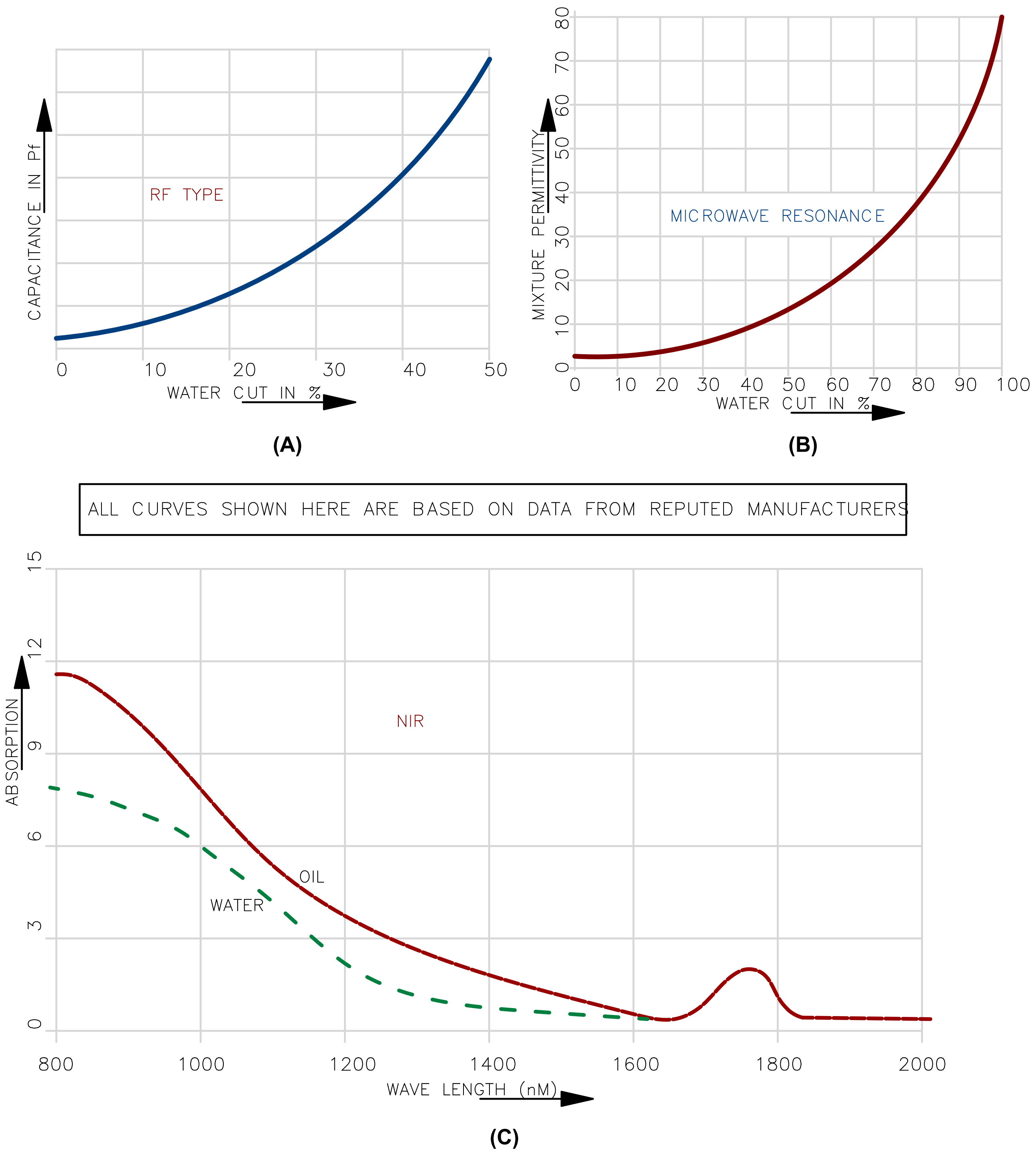


FIGURE IX/2.3.0-1 Water cut meter characteristics. (A) Capacitance vs. water cut. (B) Permittivity vs. water cut. (C) Absorption of water and oil.

microwave resonance frequency. In this method, there is a correlation between the microwave resonance frequency f_r and the mixture permittivity ε_{mix}. If the microwave resonance frequency with an empty sensor f_0 (normally stored in a unit as a calibration constant), ε_{mix} hence the water content can be found by utilizing Eq. IX/2.1.0-4. Since f_0 is stored as constant, frequent recalibration is unwarranted. However, sampling (representative) should be

used to periodically check water cut values. Insertion type RF probes cannot recognize any variance in the water content within the flow, but in this method such a limitation is not there. Emerson Roxar is an example of this type [26]. Microwave measurement details have been discussed in Section 3.2.0 also. So, Section 3.2.0 may be referenced.

3. **NIR:** The measurement is based on near-infrared absorption spectroscopy, somewhat similar to low-energy gamma ray (discussed earlier). Absorption of NIR by water and oil has been depicted in Fig. IX/2.3.0-1C. Here oil and water are easily differentiated. This type of meter can offer good accuracy at high water-cut levels as well as lower water-cut measurements by simultaneously measuring **multiple** wavelengths that include both water and oil absorption peaks. Water-cut measurement uncertainties are less than 2%, even with situations of varying salinity and when entrained gas is present. Some users, like Weatherford (*Red Eye 2G*) four wavelength bands, are measured simultaneously to deliver accurate readings. These wavelength bands can be optimized for various applications [27].

Referring to Fig. IX/2.1.0-1D it can be seen that it is possible to find water cut gamma radiation also, somewhat similar to a microwave signal.

2.3.2 WATER CUT METER FEATURES AND APPLICATIONS

In this section features of the available meter and their applications are covered.

1. **Features:** The following are the major features available from the various meters in the market.
   - It is possible to measure water cut at high temperature and pressure ratings. Pressure rating >100 kg/cm^2 and temperature up to nearly 230°C water cut meters are available.
   - Most water cut meters are easy to configure and install.
   - Water cut meters normally provide a local display for operational help and they offer good choices of interfaces with other systems in addition to standard 4−20 mADC output.
   - Checking of water cut meters is recommended but many offer meters which do not need periodic recalibration.
   - Some meters offer immunity to *paraffin* buildup. The majority of meters available on the market offer suitable measures for *salinity* and *top cut*.
   - Response <1 s is common.
   - Most meters are suitable for hazardous applications.
   - Water cut meters are available with long-term stability and accuracies accepted for fiscal measurements.
   - Meters up to ∼900 mm are available.
2. **Application areas:** Apart from application in well monitoring and other oil and gas applications, it is found in other application areas also as listed here:
   - Automatic well testing (AWT);
   - Well monitoring and testing;
   - Basic sediment and water (BS&W);
   - Oil pipelines and refinery pipelines;
   - Crude feeding;
   - Separation vessels;
   - Crude oil tank dewatering;
   - MPFM applications;
   - Shipping lines;
   - Net oil production;
   - Lease automatic custody transfer (LACT);
   - Pump protection;
   - Dielectric analysis.

2.3.3 WATER CUT METER SPECIFICATION

A brief specification of a water meter has been provided in Table IX/2.3.3-1. From the discussions in Section 2.3.1 it is clear that there are a number of types of meters, so there will be different features in different types. Therefore, the general functional specification part only has been elaborated in Table IX/2.3.3-1. In the table, the maximum possible data have been accommodated, however all data may *not go together*. Based on the application, the manufacturers' data may be referenced.

TABLE IX/2.3.3-1 Brief Specification of Water Meter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Technology	RF capacitance/microwave resonance/NIR		
2	Type*	Low cut/high cut/full cut		*Low/high cut types: Inline/top cut
3	Range (%) Inline/(top cut)	0–30/(general) Low cut: 0–1/(15) High cut: ± 0–1/(50) Full cut: 0–100		
4	Response time	<1 s (0.7 typical)		
5	GVF range	0%–100% available		Ref: Subsection 2.3.4.5
6	Max. pressure	>100 bar		
7	Max. temp.	>230°C		
8	Material	Stainless steel/copper-free aluminum		
9	Connection	Flange of rating suitable for application		
10	Sizes	Possible up to nearly 900 mm		
11	Output	4–20 mADC, alarm and other digital I/O, RS 232/485 link, HART protocol. AI/AO optional		
12	Local display	Digital LED/back-lit LCD display		
13	Power supply	Normally 24 VDC but AC supply possible		
14	Enclosure class	IP66 possible		
15	Accuracy	Wide variation from +0.05% to 5% AR based on type and range selected. Hi/low-cut inline meters offer better accuracy		
16	Repeatability	0.01%–0.1%		
17	Optional item	Densitometer		
18	Special feature			If any

2.3.4 WATER CUT METER DISCUSSIONS

There are a few important issues associated with water cut meters in this section, which will be briefly discussed to complete the discussions on water cut meters.

1. **Auto zero:** It is a patented feature with a particular meter type but is very useful. It can accept density input from a densitometer to compensate for changes in fluid density in real time, meaning it uses live density for testing [26].
2. **Low/high and top cut:** Low cut (LC) and high cut (HC) in water cut meters refer to an upper limit (span) for the water cut meter, normally these are 0%–15% and 50%, respectively. The top cut function enables measurement, using a *density* calculation for the cases when the meter is out of range.
3. **Salinity compensation (for FC):** Salinity is a function of the full cut (FC) meter, and hence is not really applicable for RF-based capacitance meters, which do not operate

in full cut range. In full cut of microwave resonant type meters this feature is retained to compensate for the salt content in the water fraction. The meter interprets the microwave signal to find the salinity of the water, and then makes use of this to produce accurate measurements [26]. In the case of NIR, this is not really applicable. In NIR, water absorption is based on the water molecule itself, not the dissolved salts.

4. **Emulsion handling:** As discussed at the beginning, there can be W/O emulsion which would try to scatter light in addition to light absorption, so, in NIR suitable measures are taken to nullify this scattering effect.
5. **GVF effect:** At up to 5% there is no effect, and up to 20% there is a minimum effect from GVF [27]. Beyond that there can be some effect for which multiple wavelength measurements are carried out. Normally GVF are <20%.
6. **Meter selection issues:** The following are *major* issues to be considered for meter selection:
   - *Line details:* size, material, schedule (rating);
   - *Fluid condition:* type of fluid, maximum pressure and temperature;
   - Environmental condition;
   - Area classification details;
   - *Flow:* Maximum/minimum range, fluid type;
   - Water content probable range (%) 0−1, 0−25, 0−50, 0−100;
   - GVF content (ref: 2.3.4.5 also);
   - *Connection flange:* type, standards, pressure rating, size;
   - Indication and output requirements;
   - Mixing requirements;
   - Others as applicable.

With this the discussion on water cut meters comes to an end and we now investigate virtual measurement systems.

2.4.0 Virtual Metering System (VMS)

As indicated during the initial discussions in Section 2.0.0, this is a newer concept to monitor the well optimally, i.e., for production optimization. Measurement of gas, oil, and water in the field under changing flow regime is not an easy task! It is rather a challenging one. MPFM used in modern era is quite costly, especially in subsea conditions. Therefore, virtual metering systems (VMS) are becoming increasingly popular, e.g., “iGLO” for Intelligent Gas Lift Optimization of Shell Malaysia and Petronas. VMS helps in driving down the uncertainty in measurement by providing additional data for cross-checking. Also, for well rate estimation, where the main aim is to provide awareness of well flowing conditions on a frequent basis, VMS can continuously provide estimation of multiphase well rates utilizing models and indirect sensors.

2.4.1 PRINCIPLES OF A VIRTUAL METERING SYSTEM

The exploitation of a remotely located field with expensive infrastructure, in addition to the availability of sensors and technology, have motivated people to develop so-called VMS.

Virtual metering is basically a mathematical model in which process conditions are inputted for mathematical simulation and estimation of flow rates of individual components, instead of physically measuring them using an actual physical meter. Virtual meters are used in lieu of MPFMs with higher uncertainties. Virtual metering is a special case of a broader class: “virtual sensors” [28]. Only for creation and once calibration of virtual metering one needs to have physical flow only for a while. After calibration, the virtual meter can use process conditions to make the necessary estimates. At the time of “on-test,” there will be well operating conditions and production for a particular well. These data are used to calibrate theoretical and/or data-driven nonlinear regression models [28]. As a next step, the cause-and-effect relationship needs to be established so as to put the model on-line using the current well operating conditions.

2.4.2 BASIC PROCESS OF A VIRTUAL METERING SYSTEM

As already mentioned, the basic principle of VMS is that there will be a typical pipeline

model. This pipeline model is fed with real-time measurements from the control system, such as a plant digital control system (DCS), which could be a simple PLC or networked supervisory control and data acquisition (SCADA). Real-time data are fed into the model so as to simulate the process state in the pipeline model in real time. During the development of the real-time fluid flow metering model, a number of down-hole crude oil ***samples*** need to be obtained, as they are required for pressure, volume, temperature (PVT) analysis. From the analysis of PVT data, gas, oil, and water densities, volume fraction of gas, oil and water, specific gravity of gas and API of oil, and solution gas oil ratio at different temperatures and pressures are obtained. As shown in Fig. IX/2.4.0-1, the gas, oil, and water densities are changed from a test condition to an actual condition based on PVT data.

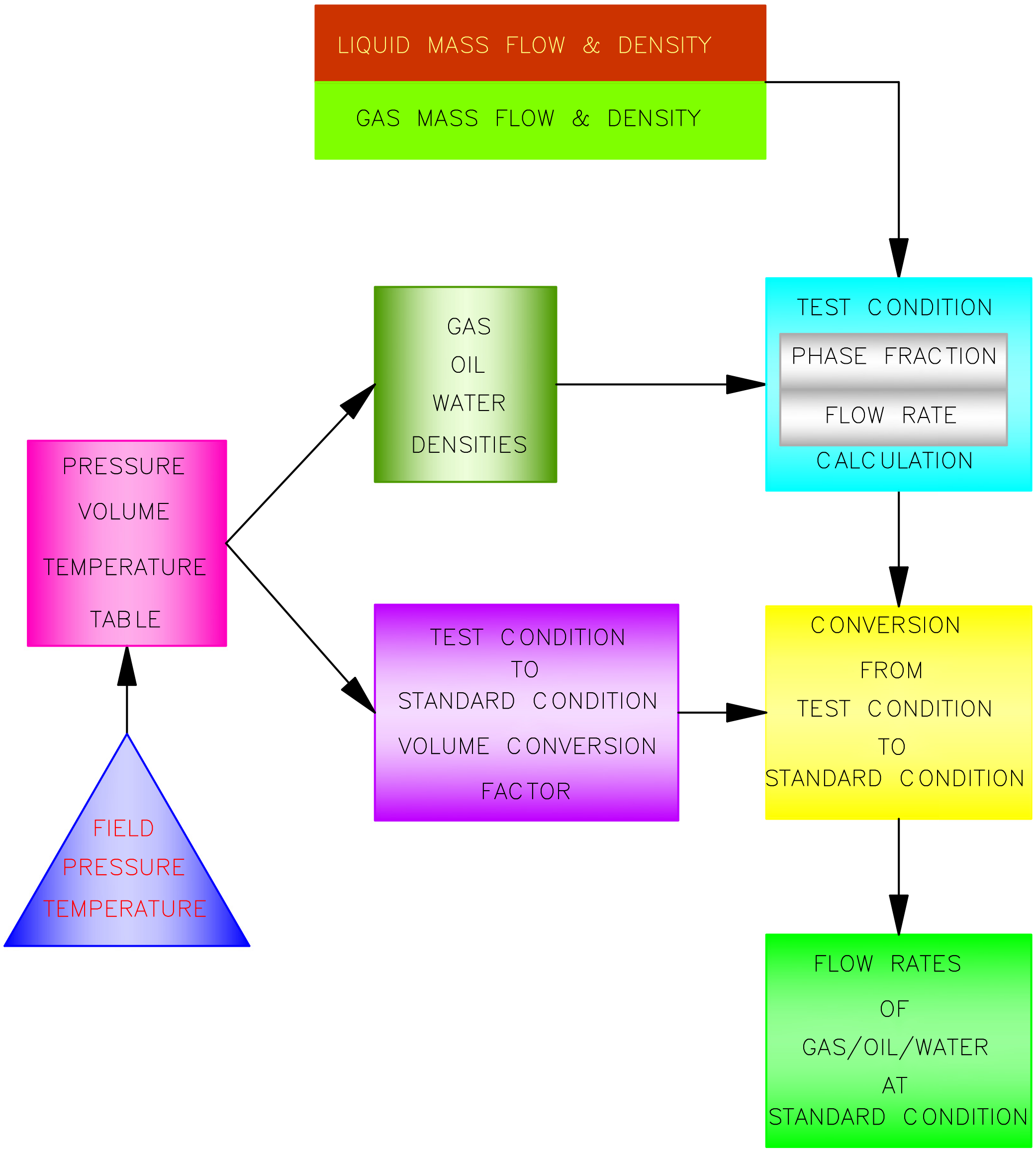


FIGURE IX/2.4.0-1 Virtual measurement concept.

Similarly, the volumes are converted from test condition to standard condition based on the PVT data as shown. As a result, individual component flow rates at standard conditions are obtained. Real-time simulations of MPFM measurements are taken at the pressure and temperature of the fluid passing though the metering system. These measurements at actual conditions are the backbone of the principle behind the virtual metering systems and techniques. From the results generated by the real-time MPFM necessary corrections and adjustment for virtual metering system can be done. Then through actual modeling and various conversions, the flow rates at standard condition of pressure and temperature measurements are obtained. The challenge of real-time MPFM in exploration well monitoring and optimization is to resolve the uncertainty of the well conditions so that the monitoring operation may be carried out in a controlled and safe manner [29]. Field measurements of pressure, temperature, fluid properties, etc. can provide the needed information to resolve much of the uncertainty. Hence, having this information available for use during well testing enables one to safely and confidently conduct the well test operations [29].

2.4.3 ANALYSIS OF VIRTUAL METERING SYSTEM RESULTS

The real-time multiphase test results are found to be authentic and accurate because of the continuous flow rates recording with all the instantaneous variations of conditions. It has been found that in this case the uncertainties associated with physical MPFM are well removed. It has been reported that the real-time MPFM data have also enhanced monitoring of well performance, production optimization, and reservoir management. VMSs have been well recognized to cater to the critical needs of alleviation of production decline, production optimization, and to reduce capital and operating costs. This is clear from a quotation "*This gave them insights about where oil, gas and water were coming from in real-time. The asset manager immediately discovered 'Lost Oil'… Previous to this, test rates did not sum to production rates, a notable amount of oil had 'gone missing.' But now, with visibility of production in real-time, the asset manager could see how, and where, co-mingled streams' interactions decreased overall production compared to test*" [28]. Virtual meters also need maintenance on account of changes in well and reservoir depletions with time. For maintenance it is necessary to carry out well tests for comparison of result from virtual meter and actual physical meter in well testing. Thereafter necessary adjustments (or *re-field-fit* the model) to be carried out.

The discussions so far presented have been on fluid mechanics and various multiphase measurement systems. The discussions were mainly on how the various measurement constraints could be met by miscellaneous measurement systems and so the operational targets are met. In the next section short discussions on various technological details, which are exploited in various measuring systems, will be presented.

3.0.0 MULTIPHASE FLOW METERING TECHNOLOGIES

From the discussion on multiphase flow metering made so far, it is clear that when phase fractions of each phase are known and velocities are known it is easy to get the flow of an individual component. Also, various discussions have been put forward with principles for getting phase fractions and/or velocities required to compute the individual component flow rate. In this section brief discussions shall be presented on various technologies behind such measurements.

This discussions supplement the various technologies already covered in Section 2.0.0. Of the various instruments deployed in multiphase flow measurement, a few are conventional instruments. These are tagged as conventional in the sense that they are standard instruments normally deployed for measurements of standard single-phase fluids. DP elements, PD meters, electromagnetic flow meters, US flow meters, turbine meters, vortex meters, and Coriolis mass flow meters are a few that fall under this category. Also, the technological details behind flow measurements through them have already been covered at length in previous sections and chapters, e.g.:

- **DP elements and DP-based meters:** Chapter II;
- **PD meters:** Chapter IV;
- **Velocity type:** Electromagnetic, US, turbine, and vortex meters: Chapter V;
- **Coriolis mass flow meters:** Chapter VI.

The chapter reference against each type of meter has been specifically mentioned so that as necessary reader can recap the discussions therein.

We now recap these so-called conventional instruments one by one and to see how these technologies have been utilized in multiphase flow metering.

1. **DP measurement:** I have used DP measurement intentionally, to bring to the notice of the reader that DP measurement can be used as one of the measurements listed in Table I/3.4.3-1, where DP elements are used. On the other hand, DP measurement can be deployed to find the void fraction, as shown in Fig. IX/1.2.3-2. In this case there is no deployment of the DP element for the measurement. On the other hand, in cases of DP as MPFM mentioned in Table I/3.4.3-1, there will be one DP element to complete the measurement. For this reason, DP measurement has been used. However, in this section we are interested in multiphase flow measurement. We now discuss the DP elements and transmitters.
   - *DP element:* Venturi tubes, orifice plates, and V cones are normally used as one of the measuring means for multiphase measurement.
   - *DP measuring transmitter:* This could be a multivariable transmitter.

   For wet gas measurement DP elements have a great role to play, in fact in most cases a DP element is used. For DP type measurement, the necessary correction factors should be taken care of based on the type of DP elements used. For DP measurement as a part of multiphase flow measurement, multivariable transmitters are always preferred because it is possible not only for DP but also pressure and temperature of the flow line. Pressure and temperature conditions are important to gather the operating condition of the measurement. In most commercial wet gas meters MVTs are used, as shown in Fig. IX/2.2.3-1. Refer Chapter XI for details on DPTs/MVTs)
2. **PD meters:** As seen in Subsection 1.3.2.1, separation mode, or for velocity (flow) measurement PD meters are used (refer to Section 2.1.0) for measurement of liquid/gas. Normally oval gear, vanes, gears, and piston meters are used as PD meters. PD meter types have been discussed in Chapter IV.
3. **Turbine meter:** As mentioned earlier, for multiphase measurement turbines are not very popular on account of the risk of damage to the bearing due to presence of solid in the multiphase flow. However, often these are used for gas flow measurement.
4. **Vortex meter:** Vortex meters are used for velocity measurement of gas. However there is a possibility of over-reading already discussed.
5. **Electromagnetic flow meter:** Based on the application, whenever there is minimum conductivity in the liquid, electromagnetic flow meters are often used for measurement of phase velocity, as shown in Fig. IX/1.2.3-2.
6. **US flow meter:** This noninvasive meter is also used for measurement of velocity in multiphase measurement but it suffers from overreading (refer to Subsection 1.2.4.2).

7. **Coriolis meter:** Coriolis meters can measure both mass density and hence volume flow. However, the presence of gas creates measurement errors (refer to Subsection 1.2.4.1).
8. **Cross-correlation:** In signal handling and processing, cross-correlation is a measure of the similarity of the two as a function of the displacement (in time frame) of one relative to the other. Cross-covariance or cross-correlation provides us with the similarity of two signals, commonly used to find an unknown signal by comparing it to a known one. Fast Fourier transform (FFT) is often used in computing algorithms by taking FFT of the signals, i.e., carrying out the algorithm in the frequency domain to find the fast correlation. Finally, after finding the required signal function, an inverse FFT may be applied to get the signal in the time domain In this connection Subsection 1.2.4.3 may be referenced.

Based on this principle in multiphase flow measurement velocity, for example, could be calculated. This principle has already been discussed in Section 8.3.0 of Chapter I.

Flowing signals produced in multiphase flow (of a gas-oil-water mixture) can be used in the correlation measurement to change the problem of the measurement of velocity into the problem of measuring the time interval or transit time. Cross-correlation measurement techniques have become widely used means to measure the rate of change of flow in the pipeline. It makes use of the transit time of a tagging signal in the fluid flowing through a pair of parallel-mounted sensors on the pipelines. The resemblance of two waveforms is measured by cross-correlation as an assignment of a time tag applied to one of them. As is shown in Fig. IX/3.0.0-1A the same kind of sensors [upstream (UP) and downstream (DN)], are installed at a distance of L, along the flow pipe. When multiphase fluid flows through the sensors, each of the sensors will produce an output. Let the two signals be x(t) and y(t). As the flow passes the two sensors, the signal pattern measured by the first sensor will be repeated at the downstream sensor after the short period of time it takes the flow to travel from the first (upstream) to the second (downstream) sensor. The time lag between the signals is named the transit time, τ_0, i.e., $y\ (t+\tau_0) = x(t)$; cross-correlation function $R_{xy}\ (\tau)\ \tau$ is written as

$$\begin{aligned} R_{xy} &= \lim_{t \to \propto} \frac{1}{T} \int_0^T x(t)y(t+\tau-\tau_0)dt \\ &= R_{xy}(\tau-\tau_0) \end{aligned} \qquad \text{(IX/3.0.0-1)}$$

$R_{xy}\ (\tau)$ reflects the interaction and similarity of the two waves described as x(t) and y(t). Here, we know from the characteristics of the correlation function that R_{xy} (xy) obtains the maximum value when $\tau = \tau_0$, so, the peak of the correlation function R_{xy} (y) corresponds to the time value, τ equals the transit time τ_0. The distance between the two sensors is known, L, then if A stands to represent the cross-sectional area of the pipe, then for velocity v, one can write

$$q = A \cdot v = A \cdot L / \tau_0 \qquad \text{(IX/3.0.0-2)}$$

As all these results are obtained under ideal conditions, we must consider various other conditions, including noises which will contribute to measurement error. As stated earlier for computation, in an algorithm we need to take the help of FFT to improve the computing speed and the real-time, and we can also obtain a higher precision. As a result one can see the correlation as shown in Fig. IX/3.0.0-1B. At this point it is important to note that this is a mathematical way of finding the required variable. Here, two sensors/transducers should be similar so that transit time discussed above could be applied.

Other technologies will be discussed in the following sections. These discussions start with the application of sonar in MPFM.

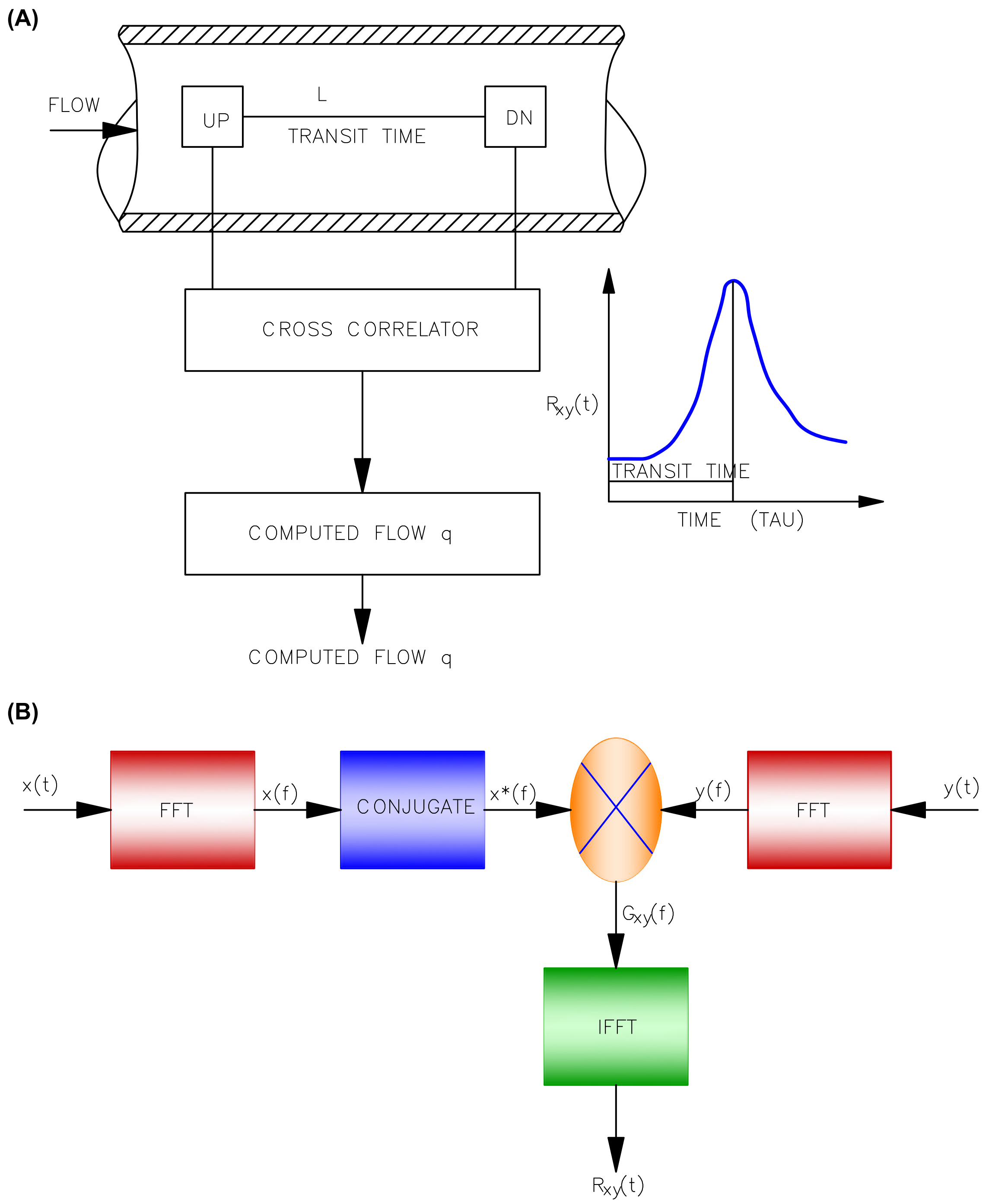


FIGURE IX/3.0.0-1 Cross-correlation in multiphase flow. (A) Cross-correlation application. (B) Computation by FFT (IFFT = inverse FFT; for conversion of function from frequency domain to time domain).

3.1.0 Sonar in MPFM

Measurement of volumetric flow by sonar has been discussed at length in Section 9.0.0 of Chapter V. Hence, the working details of the same need not be repeated here.

As indicated in Chapter V, clamp-on, sonar-based flow measurement technology exploits simultaneous measurements of volumetric flow rate and process fluid sound speed. The technology utilizes sonar array processing techniques

to perform two independent measurements to characterize the process fluid for both single-phase and multiphase flows. According to the measurement technology, the meter provides mixture volumetric flow by tracking the speed at which naturally occurring flow-generated vortical pressure fields convect past an array of strain-based sensors clamped on to the existing process pipe. We know that the speed of sound is related to the density of the medium. Therefore, the meter also provides compositional information by measuring the speed of sound waves propagating through the process fluid using the same clamped-on sensors. In the case of multiphase measurements it helps to get an accurate void fraction, i.e., the process sound speed to accurately measure the amount of entrained gases in liquid−continuous mixtures.

The velocity of sound thus determined is a very sensitive indicator of the process aeration and it offers a superior alternative for complex measurements in slurry and multiphase flows. The propagation of acoustic waves occurs at frequencies much above the frequency domain of vortical pressure fluctuations. The wavelength of sound is larger than the pipe diameter and hence also significantly larger than any process inhomogeneities, such as bubbles.

As the velocity of sound in a fluid equals the square root of the compressibility over the density, the two mixing rules can be written as:

$$\frac{1}{\rho c^2} = \frac{\varphi}{\rho g c_g^2} + \frac{1-\varphi}{\rho_l c l^2} \qquad \text{(IX/3.1.0-1)}$$

where φ is the volume fraction of gas at line conditions, c is the speed of sound in air, ρ the density, and the subscripts g and l refer to the gas and liquid phases, respectively. Here two phase conditions have been shown. This is equally applicable for a gas/oil and water mixture also. Therefore the same sonar processing can be applied to determine both the acoustical velocity and the vortical velocity at the same time. Under moderate temperature and pressure line conditions, the density is dominated by the liquid density. As such, it will be necessary to measure the process pressure (when varying) as both the gas density and the liquid density are significant when determining the gas volume fraction from the mixture sound speed. Determination of the gas content using the mixture speed of sound is independent of gas type and accuracy will be unaffected. Sonar flow meters are capable of meeting the challenges for multiphase flow measurement in the oil and gas industry. Sonar meters measure the propagation velocity of operationally generated sound in the ∼100−1000 Hz frequency range. In this frequency range, sound propagates as a one-dimensional wave, using the process pipe as a wave-guide. The wavelength of sound in this frequency range (>1 m) is typically several orders of magnitude larger than the length scale of any bubbles or flow nonuniformities. The long wavelength acoustics propagate through multiphase mixtures unimpeded, providing a robust and representative measure of the volumetrically averaged properties of the flow.

Accurate measurement of the net oil rate from individual wells is a crucial issue which must be addressed properly for effective oil field management, production optimization, and financial allocation issues. The contribution of sonar in correct net oil measurement is immense. Normally net oil measurements are carried out by a Coriolis density meter (not very stable in the presence of gas as already discussed), microwave resonance, and microwave absorption. In all such measurements of oil cut, there will be over-reading if there is the presence of gas. Sonar can be used in these cases to take care of over-readings. Use of sonar in wet gas measurement has already been discussed in Section 2.2.3. Therefore, the discussions can be concluded with the note that sonar technology helps in many ways the measurement of multiphase flow.

3.2.0 Microwave Measurements in Multiphase

Microwave measurement technique and its difference with capacitive measurement as already discussed in Section 2.3.0. In the case of capacitance measurements RF signals are used whose

frequencies are lower than microwave signals. Also, in the case of the microwave measurement technique either a change of frequencies of resonance due to permittivity is measured or absorption of microwave energy by the medium is measured. Different materials have different permittivities, and the permittivity of a mixture depends on the permittivity of the components and the composition. By measuring the permittivity of the mixture, one therefore gets information about the composition. This is especially so in the case of a mixture of gas/oil and water, because there are vast differences in the permittivity of water with respect to that of oil, and this is a major reason why microwave technology finds major applications in water cut meters. In general, permittivity is influenced by factors like temperature, density, and structure (e.g., the shape of the inclusions in a host material). When there are more than two components in the mixture (e.g., oil, water, and gas), the number of unknown parameters increases. In such cases multiparameter microwave measurements (e.g., resonant frequency and quality factor or, insertion loss and phase) [30] or other types of sensors in conjunction with this must be used. Prior to proceeding further, we look into the features, i.e., pros and cons, of measurement by microwave technology.

3.2.1 ADVANTAGES AND DISADVANTAGES OF MICROWAVE MEASUREMENT TECHNOLOGY

Microwave technology enjoys some distinct advantages over other technologies involved in multiphase flow measurement, however it has some limitations also. In this section these are highlighted.

1. **Advantages:** Listed below are a few advantages of microwave technology:
   - *Nonintrusive and noninvasive:* Microwave sensors are nonintrusive and noninvasive sensors, so they can usually perform measurements from a distance, without interfering with the process;
   - *Stability:* On account of dependence of resonant frequency on physical dimensions of the sensor it is stable in almost all conditions;
   - *Penetration and volume measurement:* Except metals, microwaves can penetrate all materials, making it possible to carry out measurements on the volume of the material, not the surface alone;
   - *Permittivity difference of water:* In multiphase flow measurement, microwave sensors find great contrast between water and other materials, hence they are well suited for measurement of water content;
   - *Safety:* When compared with gamma/radioactive sensors, microwave measurements are much safer. This type of sensing is faster than its counterpart with radioactive sensing;
   - *Material degradation:* Measurement utilizing microwave technology, never affects the material under test;
   - *Environmental effect:* Microwave sensors are relatively insensitive to environmental conditions, such as humidity and dust. Also, sensors are less sensitive to material build up and hence are usable in slurries;
   - *DC resistance:* At microwave frequency of measurements DC conductivity almost disappears, hence measurement is relatively insensitive to temperature and ion concentration;
2. **Disadvantages:** Listed below are a few disadvantages of this measurement type:
   - *Cost:* The cost of measurement which goes up with higher frequency (for better results) is quite high;
   - *Spatial resolution:* On account of long wavelength, spatial resolution achievable is less;
   - *Separate calibration:* For each material separate calibration is essential for better results;
   - *Compensation:* On account of its sensitivity to more than a single parameter often it is necessary to compensate the same with the help of other sensor type(s);
   - *Universality:* Measurement type is application-specific, hence there is less universality [30].

3.2.2 THEORETICAL BACKGROUND FOR MEASUREMENT

Microwave technology deployed in multiphase flow metering is mainly to determine void fraction and water cut. Of these two it is found more often in water cut measurements. Three physical properties are mainly exploited in microwave technology for multiphase flow metering systems. These properties are *frequency* (of resonance), *change in wave length*, and *attenuation*. Water content measurement by the microwave attenuation method is not only used in multiphase flow in oil and gas but is also used to measure water content in amorphous mixtures like margarine. So, in microwave measurement, there a generation source, detector, and computing system which analyzes the signal from detector(s) are required to give the results in a desired format. Therefore, the interaction between microwaves and the medium of propagation is completely determined by the relative permittivity and permeability. ε is the electric permittivity of the material, being $\varepsilon = \varepsilon_0 \varepsilon_r$ where ε_0 is the permittivity of free space, and ε_r is the relative permittivity.

If we take ε_r and μ_r as the relative permittivity and permeability of the medium, then it can be represented by

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \quad \text{(IX/3.2.2-1)}$$

$$\mu_r = \mu_r' - j\mu_r'' \quad \text{(IX/3.2.2-2)}$$

The real portion of permittivity is responsible for energy storage (or dielectric constant) and the imaginary portion stands to represent the energy loss portion which can come from dielectric rotational loss, interface polarization loss, and resistive loss. There are various kinds of sensors used in microwave measurement. These are described here.

1. **Free-space transmission sensors:** This is a very simple configuration. There are two dielectric windows on opposite sides of the pipe on the transmitting and receiving antennae. Here the major problematic issue is reflections from various surfaces and the measurement is highly dependent on the flow regime.
2. **Special transmission sensing:** In this type there are a set of transmitting antenna and two receiving antennas at different distances apart. In this configuration it cancels out normal error from the frequency response. For better results varying frequencies are often used.
3. **Guided wave transmission sensors:** Here microwave signals can be guided by coaxial cable or dielectric waveguide. The material/ medium is brought into contact with the electric field affecting the propagation factors like phase and attenuation. In this method there will be better control over impedance matching. The sensitivity is smaller and actually measures only a small fraction of the total flow in the pipe.
4. **Reflection sensor:** The reflection sensor measures the reflection coefficient of the wave as reflected from the end of a transmission line. It can cover a wide range of frequencies and is mainly used for measurements in laboratories.
5. **Tomographic sensors:** Tomography is a technique used to *study* (in general the cross-section of a solid object) the structure of flow in a pipe. Different kinds of tomography help to study in detail mixtures of liquid and gas, the phases separately producing various flow regimes, like annular flow, bubble flow, mist flow, churn flow, and slug flow. Microwave tomography is an advanced system. Like other tomography, for example, ultrasonic tomography, which has already been discussed in Subsection 1.2.4.2, in microwave tomography a transmitter is transmitting a wave that penetrates the medium to reach an array of receivers measuring the phase and amplitude of the wave front at different locations on the other side of the medium.
6. **Resonator sensors:** Microwave resonators can be implemented in many different ways for measuring in pipes. This is typically as shown in Fig. IX/3.2.0-1A. There can be two classes of resonator sensors: one type which is filled with the medium and other with a considerable part of the field outside the medium,

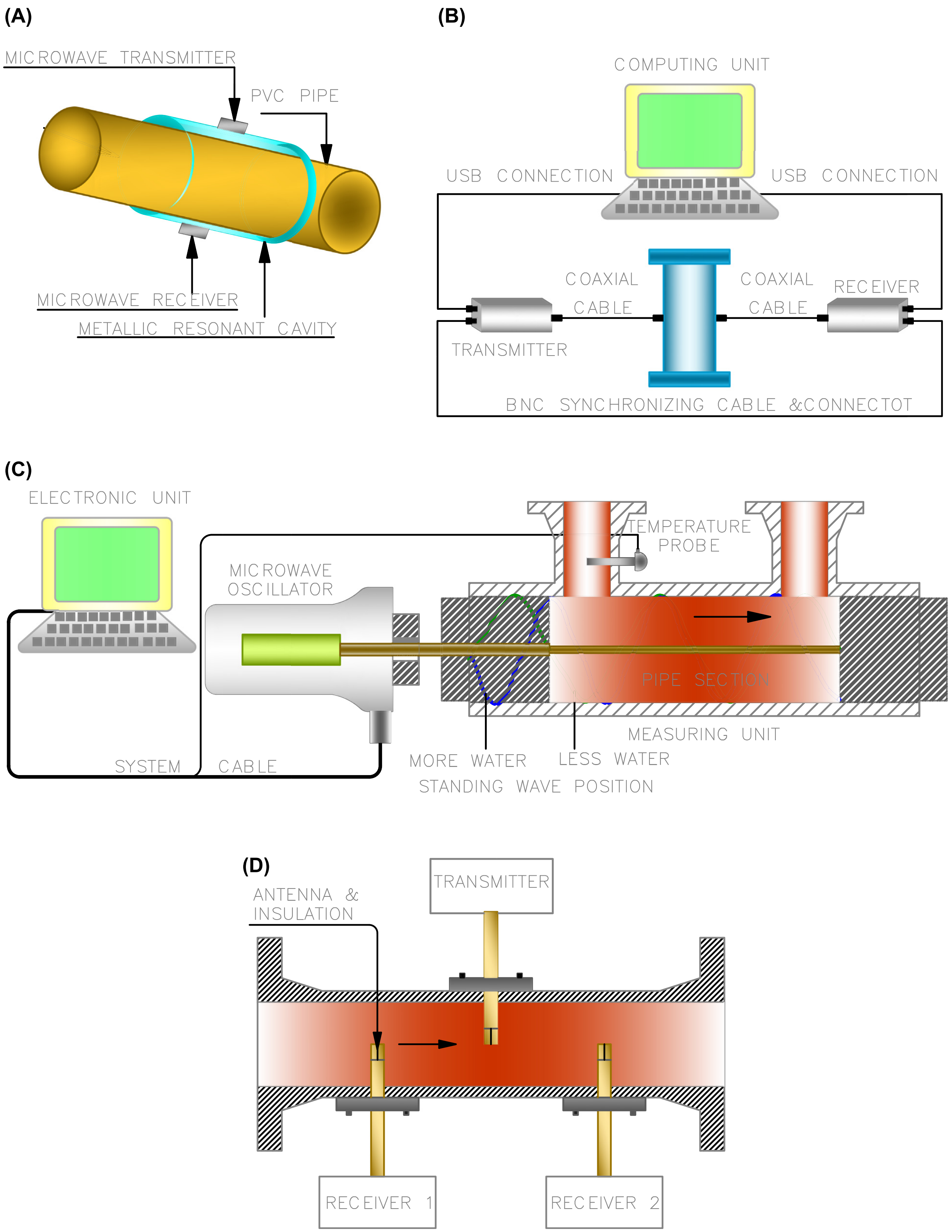


FIGURE IX/3.2.0-1 Microwave sensing. (A) Sensor configuration. (B) Microwave sensing schematic. (C) Change of frequency sensing. (D) Absorption type microwave sensing.

typically as shown in Fig. IX/3.2.0-1A. *The former type is limited to measuring materials with low losses. If the losses become too high, the resonance disappears. In the petroleum industry this typically means oil-continuous fluids (water drops in oil)* [30].

Now let us look into different types of measurements by microwaves.

3.2.3 RESONATOR TYPE SENSING

Microwave technology is based on resonant cavities that are often employed in water-cut meters. For measurement, it depends on the permittivity/dielectric properties of the multiphase medium. This technique is used in mixtures containing water, to take advantage of the large difference between the electric permittivity of water ($\varepsilon_{rw} \approx 81$ for frequencies < 1 GHz) and those of other flows such as oil ($\varepsilon_{ro} \approx 2$). This is a good method of measurement as long as there is a good amount of water. The signal starts attenuating as the water content decreases.

1. **Resonator basics:** A resonator has a natural frequency of oscillation, a resonant frequency. During resonance energy is converted from one kind to another and back, e.g., energy transfer between electric magnetic energy in an LC oscillator. Based on the condition, the resonator can store energy so that it can continuously flip between two kinds of energies at a specific speed. In a microwave resonator electromagnetic waves travel back and forth between reflecting points resulting in a standing wave pattern, where the energy *pulsates* between electric and magnetic energy. Naturally, such periodic conversion of energy from one type to another normally involves losses. The quality factor in a resonator accounts for such losses. The quality factor represents the speed at which the stored energy is dissipated. Therefore, the quality factor, Q, is defined as:

$$Q = (2\pi \text{ energy stored in resonator}) / \text{energy lost in one cycle}$$

2. **Resonant frequency computation:** Resonant cavities are closed *metallic* devices (rectangular or cylindrical shape), in which the energy is stored in the electromagnetic fields at a high frequency. The resonance occurs at distinct frequencies corresponding to different propagation modes, denoted by: transversal electric, TE_{nml}, and transversal magnetic, T_{nml}, where n, m, and l, refer to a maximum electric field at a wave pattern in the cavity directions. The resonance frequency of a cylindrical cavity can be determined by:

$$f_{nml} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \left[\left(\frac{P_{nm}}{b} \right)^2 + \left(\frac{l\pi}{d} \right)^2 \right]^{1/2} \quad \text{(IX/3.2.3-1)}$$

where p_{nm} are m-th-order Bessel functions of the first 100 kind, that vary according to the propagation mode; a is the cavity radius and d is the cavity length; μ is the permeability of the material; ε_r is the electric permittivity of the material as already explained in Section 3.2.2. A typical sensor and sensing system has been depicted in Fig. IX/3.2.0-1A and B. By replacing the sensor parameter value one would get

$$\text{Resonant frequency is given by: fr} = \frac{Kc}{\sqrt{\varepsilon_m}} \quad \text{(IX/3.2.3-2)}$$

where K is a constant for the sensor, c is the velocity of sound, and ε_m is the permittivity of mixture. Here it is noted that the resonant frequency of the cavity sensor is inversely proportional to the square root of the material's permittivity and that the permittivity varies with the fraction of water inside. This equation may be compared with Eq. IX/2.1.0-4. For the cases $\varepsilon_r' \gg \varepsilon_r''$ it is possible to get the relation as given in Eq. IX/2.1.0-4. This type is used by ROXAR meters.

3. **Operation:** With a microwave resonator it is found that when electromagnetic waves are transmitted into a particular flowing mixture there is only one peak for each percentage of

water (except for 0% of water which has two peaks). So, in a resonant type meter, when the electromagnetic waves transmit into a particular flowing mixture there will be a peak amplitude at a characteristic frequency (wavelength) which corresponds directly to the water content of the mixture. This characteristic resonant frequency is inversely proportional to the square root of the mixture dielectric constants (In this connection Fig. IX/2.3.0-1B may be referenced). The difficulty arises when the energy loss portion of the permittivity becomes significant then the measurement technique becomes inaccurate. It is very difficult to predict when the imaginary part of the permittivity becomes dominant. Microwave resonators generally have many resonant frequencies. The frequency of the excitation (source of energy to be stored) determines the frequency of oscillation, but considerable build up of energy in the resonator takes place only when the frequency of excitation is close to a resonant frequency. Normally these types of meters include one microwave device which measures the electrical properties of the flowing mixture, and a temperature sensor to measure the temperature of the mixture. The computed device connected to the measuring system provides signals corresponding to the measured dielectric constant and temperature values and utilizes the signal in computation. Emulsion is another issue. There are two kinds of emulsions: oil-in-water and water-in-oil. Even with the same water content, the electrical properties of these two types are quite different. Therefore, instruments based on these principles have their own tables, to make the necessary corrections for better accuracy and to **nullify** the emulsion effect.

4. **Constructional details:** In typical resonant type metering, there will be a PVC type pipe through which the mixture flows. This pipe has one outer metallic (conductor) coaxial transmission line, and there will be one metal rod inside. A similar type has been shown in Fig. IX/3.2.0-1A only, instead of the inner rod, two sensors are shown schematically for better understanding. However, the basic idea is the same to complete the flow path of an electromagnetic wave through the mixture. A basic measurement scheme has been depicted in Fig. IX/3.2.0-1B.

3.2.4 CHANGE OF FREQUENCY TYPE MEASUREMENT

As the name suggests in this method, a change in the operating frequency of the system is used to detect changes to the fluid permittivity. It is reported that the measurement offers a few-fold higher sensitivity than other types. However, in this method the accuracy very much depends on salinity, density, and temperature of the fluids. Therefore, prior knowledge (and field calibration) of the fluid properties is important to maintain the required accuracy. Also, knowledge about the velocity and viscosity are important to assure the homogeneous stream necessary for measurement. A phase dynamics analyzer falls under this category of measurement.

1. **Theoretical background:** In this method there will be a change in the operating frequency with the change output load of the oscillator. Such a phenomenon is often referred to as *load pull*. Here there are complimentary loads in the entire system, i.e., permittivity of the medium in the measurement section determines the output load. The circuit components in conjunction with the external load impedance determine the oscillator frequency based on the standing wave position. As already discussed, ε_{rm} (relative permittivity of mixture) has two parts: the real part (corresponding to the dielectric constant) and the imaginary part (the loss). The temperature and loss part also affects the frequency (usually necessary compensations are provided). During measurement the permittivity of the mixture provides a complex load which causes the oscillator to precisely change in frequency, proportional to the water content of the mixture but *how*? It does so by sensing the standing wave position. The electronics at the end send an electrical signal down through the fluids, which due to reflection causes the generation of a standing wave. The microwave

oscillator sends out the signal automatically, detects the change in position, and adjusts its basic frequency based on the water content in the mixture.

2. **Implementation:** There are two sets of oscillators: the oil oscillator and the water oscillator:
   - *Oil-continuous water-cuts:* frequency: 100 MHz with 200 KHz frequency change per %WC;
   - *Water-continuous condition:* 130 MHz of frequency with 50–150 KHz frequency change per %WC (depending upon water salinity) [30].

   Based on the reflected power level, the oscillator selection is carried out, i.e., due to less loss, higher reflected power levels indicate the mixture is an emulsion is and oil-continuous and due to more loss, lower reflected power levels indicates the mixture is, an emulsion and is water-continuous. The reflected power levels of the oscillator are measured by the system, and compared with a predetermined threshold. Hence, depending on whether it is above or below the threshold, such oscillator switching is done.
3. **Instrument parts:** The system typically consists of three components as shown in Fig. IX/3.2.0-1C:
   - A measurement section;
   - An electronic unit;
   - System cable.

   The measurement section comprises the following parts:
   - Pipe section;
   - Temperature probe;
   - Microwave oscillator;
   - RF connector connects the measurement section and the microwave oscillator.

Let us now take a look at absorption type sensing.

3.2.5 ABSORPTION TYPE MEASUREMENT

In this type of meter, accuracies of oil/water meters in this category are not affected by changes in salinity, density, viscosity, temperature, or velocity of the components being analyzed. These meters are available in 150 mm and above, and water cut ranges of 0%–100%. With the help of microwave absorption technology, this type of meter measures liquid-in-liquid concentrations. The major negative point in this type of measurement is a *drop* in accuracy if the mixture is not *homogeneous*, i.e., the droplet size or coating thickness can greatly affecting measurement. The fluid at the surface of the insulator dominates the effect, in particular when the fluid consists of two immiscible fluids [30].

1. **Theoretical background:** As stated above, this type of water-cut meter measures the energy absorption properties of the oil/water mixture to provide output for 0%–100% water cut. With the help of a comparator and two theoretically fed curves (one each for the oil-continuous and water-continuous phases) determines the medium category as oil-continuous phase or water-continuous phase to select the proper energy absorption data curve. The instrument consists of one transmitter and two receivers. Both the transmitter and receivers are provided with an antenna exposed to the medium. The transmitter transmits signals of specific frequency (AGAR use this type of measurement and transmit 2.45 GHz) signal. The phase difference (and/or the ratio) between the signals from two receivers are used to measure the concentration of the two measured substances. *As both receiver antennae are exposed to the same fluid in exactly the same way, by taking the phase difference of these signals, the output becomes independent of the surface coating* [30].
2. **Instrument parts:** As shown in Fig. IX/3.2.0-1D the meter consists of the following:
   - A transmitter to transmit a high-frequency signal through duly insulated antenna;
   - Two receivers spaced at distance (along the length) and connected through the antenna describe above.

The impedance of the fluid acting on the antenna varies with the electrical properties of the fluid and can affect the amount of transmitted energy.

A divider divides the outputs of the receivers and supplies a linearized output.

We now conclude the discussions on microwave technology in multiphase flow measurement and look at various other technologies.

3.3.0 Gamma Ray and Neutron Integration Technology

In this section the application of gamma ray/ X-ray and neutron technology in the measurement of multiphase flow are covered. Basic details about gamma ray measurement in multiphase flow applications have already been discussed in detail in Subsections 1.2.3.4 and 2.1.2.2. Therefore, in this section some design aspects are discussed. On the other hand, there is another new technique is Neutron activation analysis (NAA). We start the discussion with balance details of gamma ray measurement.

3.3.1 GAMMA RAY ABSORPTION METERING

It will not be out of place to recap what we have learnt so far on gamma ray measurements pertinent to multiphase flow metering. In this subsection we have established the relationship of gamma ray absorption and void fractions. Also, in Fig. IX/1.2.3-4 various possible configurations for source and detector(s) as well as applications of gamma ray in various flow regimes are illustrated. The basic relation formula for void fraction and absorption energy has been established. Let us refer to Subsection 2.1.2.2 along with Fig. IX/ 2.1.0-1 and associated equations (Eq. IX/2.1.0-1 through IX/2.1.0-3). In that subsection it has been found that there is established generalized way to find out phase fractions in Gas/oil/water. Here same will be used.

1. **Phase fraction determination:** In Eq. IX/ 2.1.0-1 through Eq. IX/2.1.0-3, we considered gas, oil, and water to be x_1, x_2, x_3 distance from the source. However, in a practical case it is not likely that there will be three components in layer form. These can be in dispersed form also. Therefore, it is better to replace x_s with the pipe internal diameter **d** and to rewrite those equations as:

$$I_A = I_{0A} \cdot e^{-(\mu_1 A\alpha gd + \mu_2 A\alpha od + \mu_3 A\alpha wd)} \quad \text{(IX/3.3.1-1)}$$

$$I_B = I_{0B} \cdot e^{-(\mu_1 B\alpha gd + \mu_2 B\alpha od + \mu_3 B\alpha wd)} \quad \text{(IX/3.3.1-2)}$$

And use

$$\alpha_g + \alpha_o + \alpha_w = 1 \quad \text{(IX/3.3.1-3)}$$

R_g, R_o, R_w, and R_m represent the natural logarithm of the count rates for gas, oil, water, and the mixture, respectively, at energies eA and eB. One could get the phase fraction from the solution of the following matrix.

$$\begin{bmatrix} R_g eA & R_o eA & R_w eA \\ R_g eB & R_o eB & R_w eB \\ 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} \alpha_g \\ \alpha_o \\ \alpha_w \end{bmatrix} = \begin{bmatrix} R_m eA \\ R_m eB \\ 1 \end{bmatrix} \quad \text{(IX/3.3.1-4)}$$

The elements in the matrix are calibration constants, i.e., determined during the calibration process by calibrating the instrument with 100% of each of the components (air for gas). From this we get phase fractions. This measurement in conjunction with Venturi can provide individual component flow, as explained in Fig. IX/3.3.1-1. We now examine the various design details for the measurement.

2. **Energy source selection:** For the study of emission and absorption of gamma rays (also X-rays), statistical methods are deployed and normally they follow a Poisson distribution. For gamma rays the following relation holds good [31]:

$$\mu \cdot d = \left(\frac{\mu}{d}\right) \cdot \rho \cdot d = 2 \quad \text{(IX/3.3.1-5)}$$

As indicated during the initial discussion in Section 1.2.3 of this chapter, μ represents the linear absorption coefficient which is dependent on the process condition, i.e., pressure

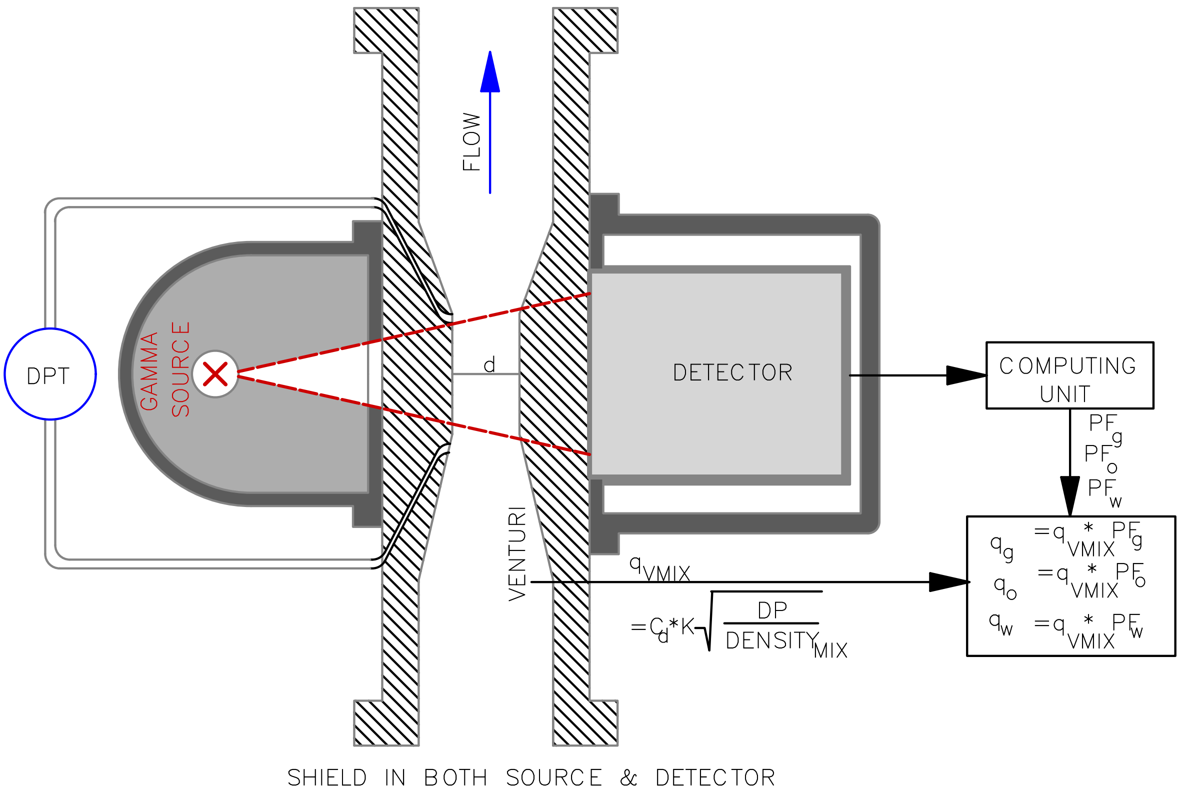


FIGURE IX/3.3.1-1 Gamma ray and Venturi. C_d, discharge coefficient; *g*, gas; *K*, constant; *MIX*, mixture; *o*, oil; *PF*, phase fraction legend for suffix; *q*, flow (volumetric); *w*, water.

and temperature. Here (μ/ρ) represents the mass absorption coefficient, which is independent of the process condition. As a consequence, the uncertainty of measurement is dependent on the process condition and of course pipe internal diameter (distance between the source and detector). In dual-energy design it is important to select the low and high energy level sources. Listed in Table IX/3.3.1-1 are some commonly used materials.

Normally, a low energy source in the range of 10–30 keV is chosen. Am-241 is also an alpha emitter. The high energy level should be higher than 40–50 keV [31].

TABLE IX/3.3.1-1 Commonly Used Gamma Sources (Not All Peaks are Given)

Isotope	Half Life	Approximate Photon Energy (KeV)
Armericium 241	433 years	12–22
Barium 133	10.8 years	30–36 to 384 long possibilities
Cesium 137	453 days	22–26
Cobalt 57	270 days	6.5–7; 14.4 even 136.5 various peaks
Cobalt 60	5.27 years	1300
Lead 210	22.3 years	94–16.4
Plutonium 238	128 days	60 Variations

3. **Detector:** For detector selection two important issues are efficiency and resolution. Sodium iodide (NaI) scintillation crystals and Si solid-state detectors are normally used for gamma ray detection. At a lower energy level efficiency the former one is much better than a solid-state detector. For a high energy level for functioning of Si solid-state detectors, a larger area may be necessary. From a resolution point of view semiconductor detectors are far ahead of other commonly used types, i.e., NaI scintillation detectors. The smaller the area detector, the better will be the resolution. Also, resolution is more critical for a low energy level. Therefore, during selection due consideration should be taken. From the discussions it is clear that there are some contradictions in the requirements for which there have been developments of dual-area solid-state detectors in practical applications.
4. **Window materials:** Low-energy gamma rays demand strong, radiation-transparent wall material. Carbon fibers are transparent as well as extremely strong and it is held by an epoxy matrix, hence Carbon fiber reinforced epoxy (CFRE) is chosen as the window material.
5. **Measurement uncertainty and allied issues:** As stated earlier, studies of the emission and absorption of gamma rays are based on statistical methods, so the uncertainties of measurement in phase fraction calculations are due to the statistical behavior of gamma rays. It has been found that absolute uncertainty in the oil fraction is the highest. In small fluid path length since there could be insufficient contrast in the absorption between the oil and the water phases uncertainty is greater. Whereas with an increase in fluid path length it decreases as it can be distinguished. The fraction uncertainty is large for a small fluid path length, as there is, but decreases as the fluid path increases up to a certain length beyond which again uncertainty increases because, on account of high absorption, the count is too small. Salinity also has a direct effect on uncertainty in measurement.

With use of dual-energy gamma rays (DEGRA) it is possible to find three-phase fractions. With an increase of another energy level, i.e., with triple-energy gamma rays (TEGRA), it is possible to detect another parameter, e.g., salinity. In this way there can be multiple-energy gamma rays (MEGRA).

While discussing gamma rays, we now look into another gamma ray spectrum in measurement through neuron activation analysis techniques.

3.3.2 NEUTRON ACTIVATION ANALYSIS—BASIC DEFINITIONS OF TERMS

Before we start any discussions we look at the term "neutron activation analysis." There exist many definitions of neutron activation analysis (NAA), which are more or less similar but may not be complete in definition, especially in the context of multiphase flow metering. Also, during discussions on NAA, there will be a number of popular terms in nuclear engineering that will be referred to. So, in order to facilitate the reader to recap these terms to understand the system better, these are also defined and explained here. But first we define NAA in the perspective of multiphase flow metering.

1. **Neutron activation analysis:** This is an analytical method used to analyze material(s) to determine chemical elements and their quantity (concentration) for the components of the test material(s) by bombarding it with neutrons to produce radioactive forms that can be identified by their characterized radiation emissions, which are indicative of elements present and their *quantity*. In most of the definitions the term "quantity" may not be used because the main aim of NAA is to find the chemical composition. On the other hand, for multiphase flow, "quantity" measurement (which is, of course, available as part of the analysis) is important. Discovered in 1936 neutron activation analysis has been in use for bulk material analysis. It is a technique used to determine the average (bulk) concentrations of all elements,

including trace elements in the test material. As part of the characterization of the test material, it also helps in determining chemical similarities or differences.

2. **Types of NAA:** With respect to the time of measurement, NAA can be categorized as: prompt gamma-ray neutron activation analysis (PGNAA) and delayed gamma-ray neutron activation analysis (DGNAA)
3. **Prompt gamma-ray neutron activation analysis (PGAA):** The **PGAA technique** is generally performed with the use of beam of neutrons for the elements with extremely high neutron capture cross-sections which decay too rapidly. Therefore, measurements take place during irradiation.
4. **Delayed gamma-ray neutron activation analysis (DGNAA):** This is the most common type and is often known as conventional NAA and is useful for the majority of elements. The technique is flexible with respect to time. The decay process is at a much slower rate than the initial de-excitation and is dependent on the unique half-life of the radioactive nucleus.
5. **Gamma ray and negative beta particles:** Of several methods of radioactive decay, gamma ray and negative beta particles are important for NAA.
   - *Gamma rays:* Gamma rays are emitted when an excited nucleus transits from a higher excited energy state to a lower energy state, i.e., when the nucleus gets de-excited. Gamma rays have well-defined energies and such emission in most cases is accompanied by nuclear reactions or decay.
   - *Negative beta particles:* Negative beta particles (β-) are basically electrons formed when a neutron is transformed into a proton during nuclear transformation. After neutron transformation, the atomic number (Z) of the resultant nucleus is one unit greater, but the mass number remains unchanged.
6. **Neutron reactions and types:** During bombardment with neutrons, the target nuclei undergo many possible nuclear reactions. There are four major reactions:
   - Neutron capture;
   - Transmutation;
   - Fission reaction;
   - Inelastic scattering.
7. **Neutron capture:** The target (material) nucleus captures (or absorbs) a neutron to produce product isotope. Naturally, there will be an increment in the mass number. If the product nucleus is unstable, it usually de-excites by emission of gamma rays and/or β- to migrate into a stable state. The entire phenomenon is referred to as neutron capture.
8. **Inelastic scattering:** Of the four neutron reactions mentioned above, inelastic scattering is an important event in our case study. In this phenomenon the target nucleus does not absorb the incident neutron, except only part of the neutron energy is transferred to the target.
9. **Neuron sources:** Nuclear reactor, cyclotron, fast neutron generator, and of course, isotopic neutron sources are major sources used in NAA for getting neutrons.
10. **Neutron flux:** The amount of neutrons available for irradiation is referred to as the neutron flux. It is expressed as the number of neutrons incident per unit area per second. Therefore, it is expressed as n/cm^2 s in CGS units.
11. **Neutron capture cross-section:** Neutron capture cross-section of the isotope leading to a specified nuclear reaction. Unit of area: barns (1 burn $= 10^{-24}$ cm).

3.3.3 NEUTRON ACTIVATION ANALYSIS PROCESS

1. **Preamble:** NAA is quite popular for quantitative multielement analysis and measurement to detect various elements, including traces or rare elements. The basic process of NAA can be well understood when the sequence of events of the process is suitably followed.

2. **Theoretical background:** The process starts by exposing the test material or sample to energized neutrons, which may be generated from any of the various sources mentioned in Subsection 3.3.2.9 or may be from a reactor. On account of the interaction between the neutrons with the test material, this causes formation of radioactive nuclei that emit characteristic gamma rays. Suitable semiconductor type radiation detectors are used for qualitative and quantitative measurement for the presence of a particular element. Detection of the specific gamma rays (of specific energy) indicates the presence of a particular element, while the area underneath the spectrum indicates the concentration of the element. For all such relevant measurements the detected data are sent to a computer for analysis and to produce the necessary result. The majority of elements can be assessed by this method. An NAA-based monitoring system requires little set-up time and space to provide data in-line. From an MPFM perspective, this monitoring system is accurate over the full range of possible oil-water-gas fractions, and is unaffected by the pressure, temperature, and flow regime into the pipe [32].
3. **Process sequence of event:** In typical NAA, stable nuclide test material undergoes neutron capture reactions on account of the incident flux of neutrons from the source. As shown in Fig. IX/3.3.2-1, on account of the interaction of neutrons with the target material, radioactive nuclides ($_{A+1}Z$), are produced. As part of the nuclear capture process, as described in Subsection 3.3.2.7, there will be a compound nucleus that forms in an excited state when a neutron interacts with the target nucleus via a nonelastic collision. The excitation energy of the compound nucleus comes from the binding energy of the neutron with the nucleus [33]. The compound nucleus is unstable, it may almost instantaneously de-excite into a more stable configuration through the emission of one or more characteristic prompt gamma rays. Alternatively, in many cases, this new configuration produces a radioactive nucleus, which also may become de-excited (or decayed) by the emission of one or more characteristic delayed gamma rays, but at a much lower rate. Thus, in this activation process, there will normally be generation of emission of a beta particle (ß-) and gamma ray(s) with a unique half-life, as a result of the decaying process. Therefore, there are two such processes, as shown in Fig. IX/3.3.2-1, namely, prompt gamma-ray neutron activation analysis (PGNAA), where measurements take place during irradiation, and delayed gamma-ray neutron activation analysis (DGNAA radioactive decay). A high-resolution gamma-ray spectrometer is used to detect energy-specific gamma rays in the presence of the *artificially* induced radioactivity in the sample for both qualitative and quantitative analysis. There is a sequence of events that happen in NAA and this has been depicted in Fig. IX/3.3.2-1.

The usual procedure involves placement of test material vis-a-vis suitable standards. In a detector the gamma ray energies are converted into an electrical signal that is processed as a count in an energy spectrum. The accumulation of gamma counts at a *particular* energy generates a curve, the area of which is proportional to the concentration or radioactivity of the characteristic radionuclide. Comparing against standards allows the establishment of a relationship that can be used to determine the abundance of a particular element or elements. *The measured count rate (R) of the gamma rays from the decay of a specific isotope in the irradiated sample can be related to the amount (n) of the original, stable isotope in the sample through the following equation [34].*

$$R = \varepsilon \cdot I_\gamma \cdot A = \varepsilon \cdot I_\gamma \cdot n \cdot \varphi \cdot \sigma \cdot \left(1 - e^{-\lambda ti}\right) \cdot e^{-\lambda td} \qquad \text{(IX/3.3.3-1)}$$

R = measured gamma-ray count rate (cps); A = absolute activity of isotope $_{A+1}Z$ in sample;

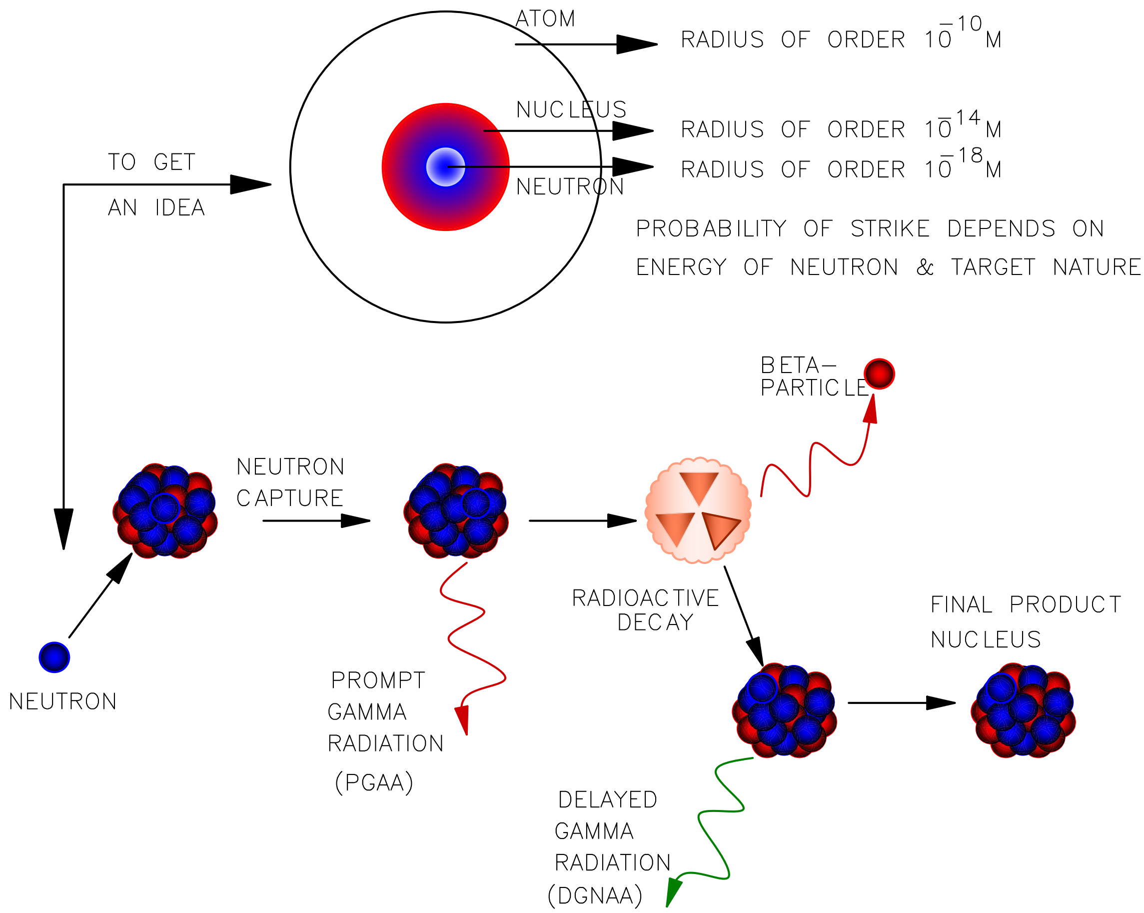


FIGURE IX/3.3.2-1 NAA details.

ε = absolute detector efficiency; I_γ = absolute gamma-ray abundance; n = number of atoms of isotope $_AZ$ in the sample; φ = neutron flux (neutrons·$cm^{-2}\,s^{-1}$); σ = neutron capture cross-section (cm^2) for isotope $_AZ$; λ = radioactive decay constant (s^{-1}) for isotope $_{A+1}Z$; ti = irradiation time (s); td = decay time (s).

When φ, σ, ε, and I_γ are known, the number of atoms n of isotope $_AZ$ in the sample can be calculated directly.

In almost all cases the count and mass element in the test material are compared with the standard, i.e., to make

$$(W_{test}/R_{test}) = (W_{std}/R_{std}) \qquad \text{(IX/3.3.3-2)}$$

where W and R represent mass element and count rate, respectively. Suffices with (R and W) "test" and "std" represent "test" (for test material) and "std" for standard, respectively. The electrical signals from the detectors are sent to the computer where these calculations are performed and after due comparison with standard data (stored in the computer) the final result is produced.

3.3.4 PROMPT GAMMA-RAY NEUTRON ACTIVATION ANALYSIS (PGNAA)

The nuclei of some elements of a test material placed in a field of neutrons absorb neutrons and are transformed to an isotope of higher mass number. This is a different kind from conventional NAA using decay of the radioactive element. As mentioned in Subsection 3.3.2.3, the PGAA technique is mainly applicable for elements with extremely high neutron capture cross-sections. These elements emit prompt gamma rays at the time of neutron capture and do not produce radioactive capture products. In PGAA, a beam of neutrons from a reactor beam port is

used. *Fluxes on samples irradiated in beams are in the order of one million times lower than on samples inside a reactor but detectors can be placed very close to the sample, compensating for much of the loss in sensitivity due to flux* [33] and make the measurement possible. A high-resolution gamma-ray spectrometer detector is used for qualitative identification and quantitative analysis of the neutron-capturing elements present in the test material. In this method measurement is carried out with the help of a semiconductor Germanium detector. Usually the beam stop is also included in the system.

3.3.5 DELAYED GAMMA-RAY NEUTRON ACTIVATION ANALYSIS (DGNAA)

Delayed gamma ray neutron activation analysis is often referred to as conventional NAA as it is applicable and useful for the vast majority of elements that produce radioactive nuclides. When the test material is irradiated, interactions of fissionable nuclei may produce radioactive products with more than one neutron emission. When these radioactive components have the capability to emit neutrons they are referred to as delayed neutron precursors (DNPs). Generally these components have a few neutrons in excess of a fully occupied, closed neutron shell, so, due to low binding energy there will be a great probability of losing them [35]. These nuclides, instead of direct neutron emission, undergo β-decay. Based on the number of atoms in the target material, a proportional number of activated atoms will be there to indicate the amount of radiation. The timing of a delayed neutron reaction is governed by the rate of β-decay. DNPs emit "late" neutrons, which are referred to as delayed neutrons. In this process there are interferences of short- and long-lived radionuclides. Interference can be improved in long-lived radionuclides by waiting for the short-lived radionuclides to decay or, in contrast, the sensitivity for short-lived isotopes can be improved by reducing the time [33]. Commonly used detectors are 3B-BF3 or 3He detectors [35]. Sampling errors, timing of irradiation, counting system, data reduction, and low efficiency of detectors are common sources of error.

3.3.6 NAA AND OIL EXPLORATION

It is interesting to note that about 70% of the oil resources in the world are heavy oil. Most of the commonly used MPFMs do not work well with heavy oil. The main problems associated with heavy oil exploration include high viscosity and low reservoir pressure. On account of this, enhanced oil recovery techniques, such as cold techniques (with sand, water flooding, vapor assistance) and hot/thermal production (steam-assisted), techniques are called for. The major reasons for nonsuitability of conventional multiphase flow metering include but are not limited to the following issues:

1. **Gravity contrast:** Since there is practically no gravity contrast between oil and water, conventional techniques are not suitable for separation, hence multiphase flow metering.
2. **Enhanced recovery method requirements:** On account of enhanced oil recovery techniques for heavy oil extraction, the MPFM must be able to cope up with a few criteria needed [32]:
   - Emulsification of fluid;
   - Foaming;
   - High temperature;
   - Entrapped gas/sand/water;
   - High water cut.
3. **NAA as MPFM:** Nondestructive NAA deals with neutrons with no charge to interact with charged particles. As is already clear from previous discussions, gamma spectroscopy is used to measure the gamma ray spectra from which it is possible to get the elemental composition and the relative amount of each element in test material. NAA can be used to measure the flow rate. As already discussed there will be production of radioactive isotopes,

which decay with a variety of half-lives. With the help of neutron pulses it is possible to activate species in the fluid. On account of flow, the activated species are transported and gamma rays from the activity are detected downstream from the activation point. The system calibration can be conducted away from the site with suitable samples [32]. With known salinity, it is possible by NAA to infer the relative presence of salts also. It is possible to arrive at the mixture fractions of oil, water, and gas, with the help of measurement of oxygen, carbon, and hydrogen composition as well as measurement of the chlorine and sulfur composition of fluid provided the salinity of the fluid is known. With NAA one can get the rate of an element flow, and density of certain elements in the conduit. The detection of many specific elements for fluid of the particular oil reservoir with neutron interrogation technique will give an opportunity to determine the combination of parameters and cross-checking of the results will give more accuracy for such a multiphase flow meter [32]. Since neutrons can penetrate the pipe wall, the installation of the device is easier and faster without any change in tubing system. Neutron interrogation monitoring systems will work reliably in a heavy oil environment [32].

From this discussion one can conclude that NAA is an effective measurement method in the area of MPFM, especially for oil and gas. With this we conclude the discussions on NAA to discuss another technology for MPFM.

3.4.0 Wire Mesh and Electrical Impedance Technology

In this section discussions are presented on wire mesh sensors and electrical impedance sensors for measurement of multiphase flow. Brief discussions on electrical impedance measurements have already been presented in Subsection 1.2.3.3 above. Therefore, the reader already has some idea about it. However, wire mesh sensing is a completely new topic, so the discussion starts with wire mesh sensing.

3.4.1 WIRE MESH TYPE MEASUREMENT FUNDAMENTALS

With the help of wire mesh sensors flow imaging is possible, so it can be used to investigate multiphase flow.

1. **Flow imaging (not tomography):** Many refer to this technology as a type of tomography. However, as tomography in principle is a *noninvasive* type of measurement and wire mesh measurement is *invasive* (i.e., electrodes fall in the path of material flow line for generation of image), it cannot be considered as a tomographic measurement. However, it can be considered as an alternative technique to the tomography systems. Compared to other technologies, wire mesh is a newer one introduced in 1998. On account of its measurement technique and data presentation technique it can be considered as an "in-between technique," lying between local phase fraction measurement and cross-sectional imaging, i.e., tomography. In any case the measurement type offers high spatial and temporal resolution [11].
2. **Requirement:** As shown in Fig. IX/3.4.1-1A and B there will be two sets of wires across the pipe cross-section, with uniform axial separation between them. Each set of parallel wires is perpendicular to the other set, as shown in Fig. IX/3.4.1-1A. One parallel set is the transmitting set and the other is the receiving set. Both transmitter sets of wires, as well as receiving set of wires, are connected to an electronic unit. At the electronic unit digitized data are processed with the help of a computer and presented for visualization and recording. It is worth noting that in the figures under reference, a schematic has been shown for conductivity measurement but it can be based on permittivity measurement also (discussed next).
3. **Types of measurement:** An electronic unit associated with wire mesh measurement measures electrical properties of the flowing medium, i.e., conductivity or permittivity. Depending on the excitation system and

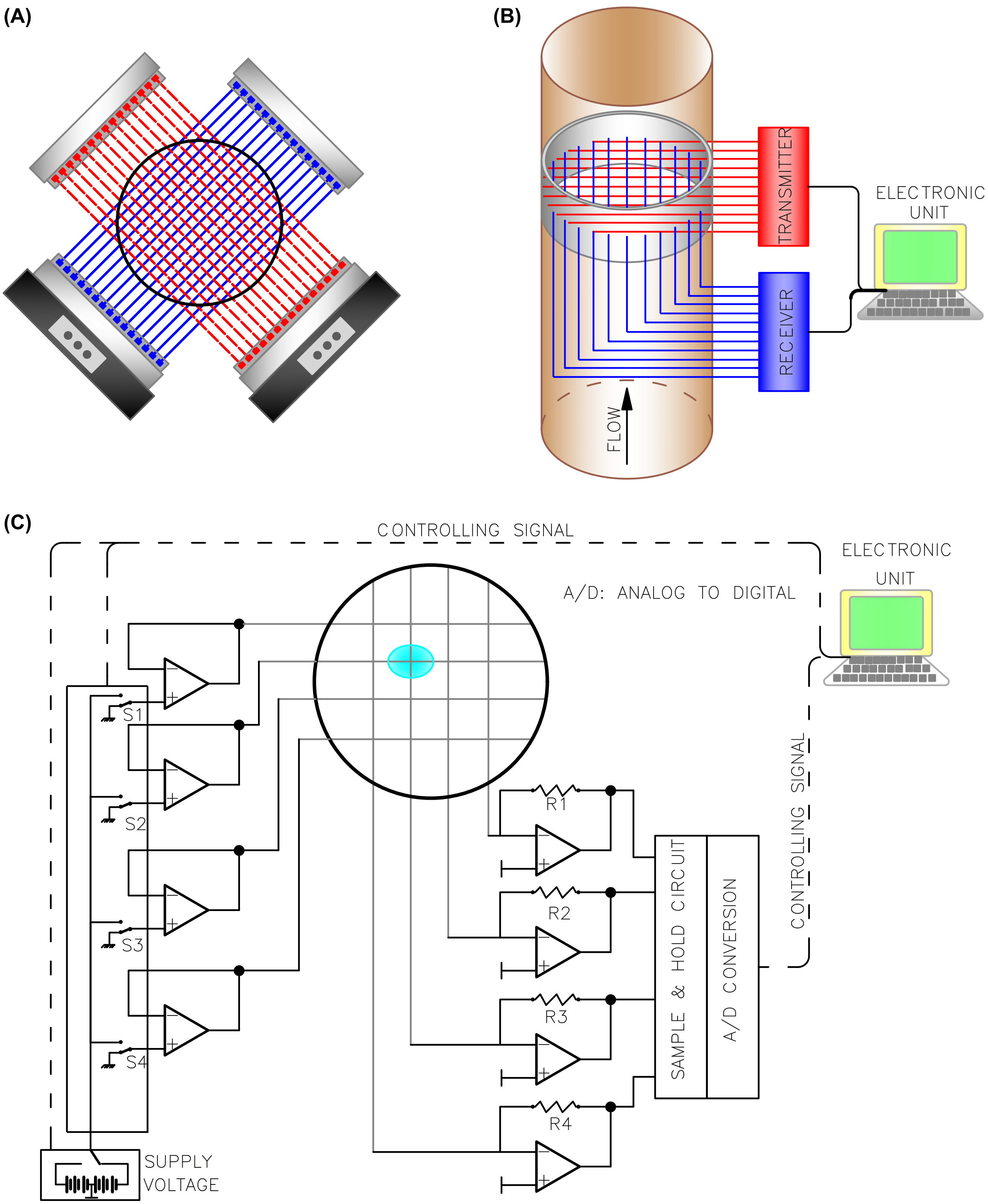


FIGURE IX/3.4.1-1 Wire mesh measurement. (A) Typical wire mesh sensors. (B) Wire mesh measurement scheme. (C) Wire mesh measuring circuit.

measurement at the electronic unit there are two types of wire mesh sensing. These are conductivity type and permittivity or capacitance type.

- *Conductivity type:* In conductivity type measurement, the transmitting wires are excited by bipolar DC voltage pulses. Therefore, receiving circuit measurement will be DC type. The electronic unit measures the local conductivity in the gaps of all crossing points at a high repetition rate. Therefore, in this type, in order to measure conductivity, in two-phase flow, one phase has to be an electrically conducting phase (conductivity $> 0.5\ \mu S/cm$) and the other a nonconducting type, e.g., water and oil. The obtained conductivity in the gap across the cross-sectional area indicates the presence of phases at crossing points.
- *Permittivity/capacitance type:* In capacitance type wire mesh, transmitting lines are excited by sinusoidal alternating voltage and receiving circuit encompasses demodulating scheme to interpret the changes in permittivity at the junction point to infer the fluid phase condition at the junction point. Therefore, similar to the conductivity type, this type also is capable of detecting phase distribution in gas–liquid or liquid–liquid fluids.

Therefore, the sensors can determine instantaneous phase fraction distributions over the pipe cross-section by measuring conductivity/permittivity in the gaps. The measurement is quite accurate and highly repeatable.

3.4.2 ELECTRICAL MEASUREMENT OF CONDUCTIVITY TYPE WIRE MESH

As indicated above, the grid circuit created by the wire mesh consists of two sets of wires, one set is connected to the transmitter circuit and the other set is connected to the receiver circuit. In Fig. IX/3.4.1-1A–C vertical wire lines (shown in Fig. IX/3.4.1-1B) are connected to the receiving circuit. The horizontal wire lines (shown in Fig. IX/3.4.1-1B) are connected to the transmitter circuit. A typical measurement block schematic is shown in Fig. IX/3.4.1-1C. In the block schematic wire mesh of 4×4 sensor configuration has been shown for explanation purposes only. Transmitter lines are taken into operation one by one in sequence. So, in order to bring the lines into sequence, one needs to use the switching circuit shown by S1 through S4 (time multiplexing) in the transmitter circuit. These are activated in sequence duly controlled from the electronic unit. As shown, nonactivated electrodes are connected to ground potential because of the chosen configuration. The current at the receiver wire is due to the activation of a given transmitter wire, and varies according to the conductivity of the fluid in the corresponding control volume close to the crossing point of the two wires (as they get connected by fluid). The currents from all receiver wires should be sampled simultaneously to get an idea of the conductivity distribution along the transmitter wire line. After the first transmitter (e.g., by S1) line sample measurement is completed, the next line is chosen (e.g., by S2) to repeat the same sampling procedure. In this manner the procedure is repeated for all transmitter electrodes. Therefore, after the last transmitter line is activated, a complete set of measurements for the whole cross-section has been acquired. Each switch measures a horizontal strip (subdivision/region) and through S1 to Sn such strips are integrated, meaning that an image of the entire cross-section is received. The measurements are in fact voltages which are proportional to the conductivity of the medium around each crossing point of the wire grid at the very moment of data sampling [11]. Each crossing point represents one subregion, meaning when S1 is ON, it measures conductivity at four subregions constituted by four receiver lines. Thus each crossing point acts as a local phase indicator. Therefore, the set of data obtained from the sensors actually represents the phase distribution over the cross-section. For explanation, only 4×4 mesh has been shown, it could be 128×128 or

more with a wire diameter as low as 0.05 mm. Nowadays, high-pressure high-temperature versions are available. The electronic unit regulates both signal generation by controlling the switching circuits and controls data acquisition also. A maximum temporal resolution of 10,000 frames per second has been made possible [11]. The intrusive effect of wire mesh sensors is mainly observed downstream of the sensors. However, the intrusive effect of this type of measurement has been discussed briefly in Section 3.4.4 below. The disadvantage of being intrusive is in part compensated by high temporal resolution, low cost, and simplicity when compared with other imaging systems [11]. As stated earlier in Subsection 3.4.1.3, in conductivity type wire mesh sensing, bipolar voltage pulses are used for sending signals through the transmission line. Thus, supply voltage shown in Fig. IX/3.4.1-1C is supplied through a switch under the control of an electronic unit. Similarly, the measurement scheme is a DC measurement scheme.

3.4.3 ELECTRICAL MEASUREMENT OF CAPACITANCE TYPE WIRE MESH

This type of measurement was introduced later to investigation the mixture containing nonconducting fluids, such as oil. Here the change in permittivity or capacitance is measured.

1. **Basic circuit description:** As stated earlier, in a capacitance wire mesh sensing system, sinusoidal AC excitation voltage is applied with the receiver to encompass a demodulation scheme. Like conductivity type sensing, transmitter lines/electrodes are activated one after another sequentially and unused ones are grounded. All current flowing from the transmitter to the receiving electrodes/lines in the other plane is measured in parallel. Through the virtual ground of the measuring amplifier, the receiving section amplifiers have only signals from the active transmitter line, as shown in Fig. IX/3.4.3-1A. Here AC excitation shown in transmitter lines/electrodes are high-frequency signals generated through a digital synthesizing oscillating circuit in the range of a few (0.1−10) MHz [11]. Like conductivity wire mesh, the AC excitation signal is switched in time-multiplexer mode to each of the transmitting lines/electrodes with the help of switches S1 through S4 (similar to that for the conductivity type). The current from the transmitting lines/electrodes is converted into voltage through the balance converting amplifier shown. Log amplifier circuitry is used for demodulation purposes. Naturally, the analog signals generated are converted into a digital signal by an analog-to-digital converter (ADC) before feeding to the electronic unit. These functions are performed with the help of a microcontroller and associated circuitry in the electronic unit.
2. **AC excitation system:** In order to get suppression of cross-talk at each crossing point to get local phase fraction in individual subregion of transmission line/electrode, it is necessary to activate each transmission electrode sequentially with the help of a switching circuit (e.g., S1 through S4) in time multiplexed mode so that only one transmitter is active at a time and others are at ground potential. As discussed earlier, all currents flowing from the transmitter to receiver electrodes at the other wire plane are measured in parallel. At the receiver measuring circuit, one end of the amplifier is at ground potential (by virtual ground), so, for each receiver measurement, it is concentrated along the active transmitter wire and the current measured at one receiver wire is only proportional to the capacitance (permittivity) of the surrounding flow phase at the crossing point. Such sequential operation of the transmitter line and ADC has been shown schematically in Fig. IX/3.4.3-1B.
3. **Permittivity assessment:** We earlier noted that the permittivities of different materials are different, naturally the dielectric constant

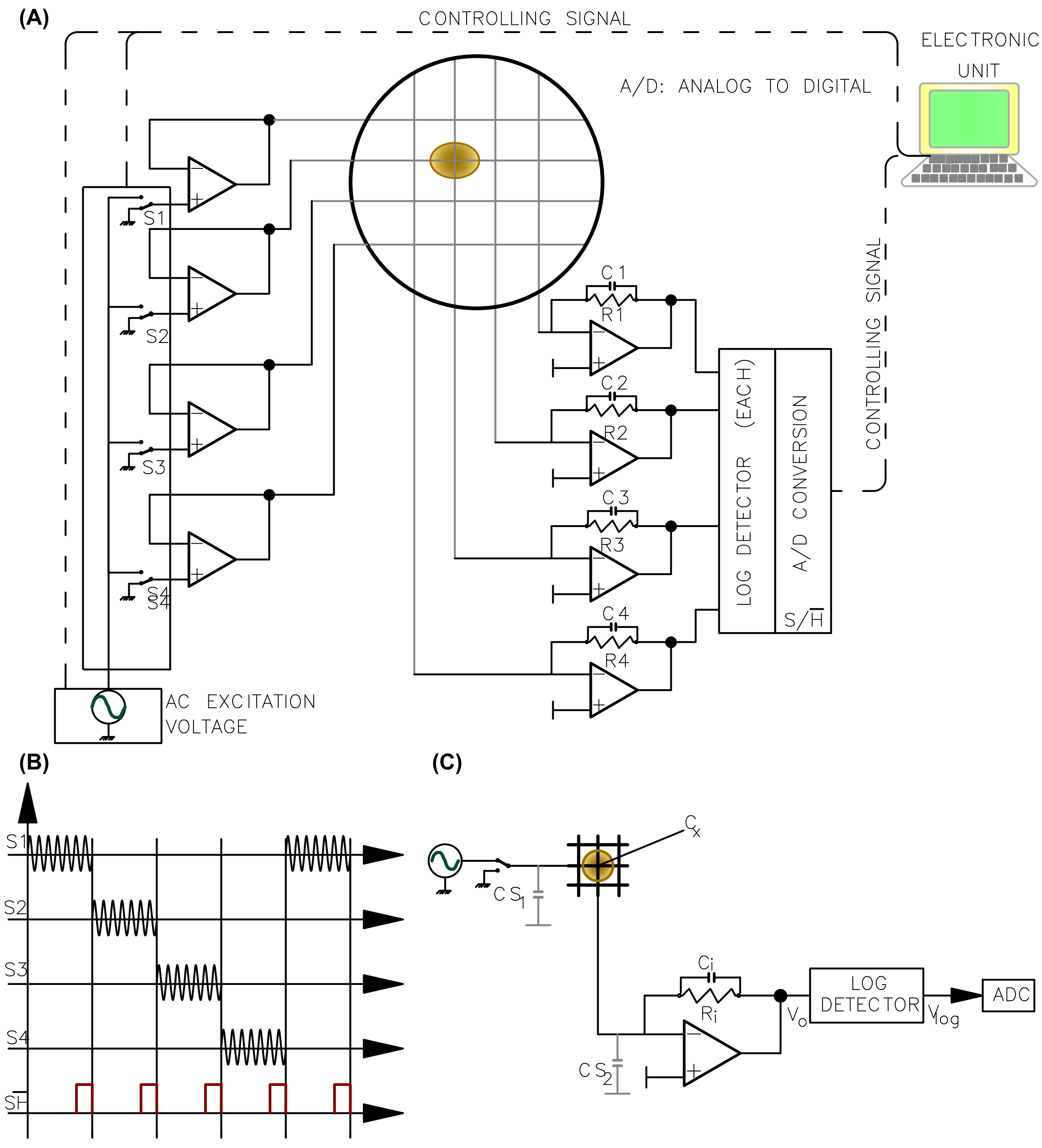


FIGURE IX/3.4.3-1 Wire mesh measurement 2 (capacitance type). (A) Wire mesh measuring circuit (capacitance type). (B) Excitation system (capacitance type). (C) Equivalent circuit (capacitance type).

and hence the capacitance offered by different materials are different. Also, it is not known what phase fraction is present at the junction. Therefore, at each junction there will be only a single unknown quantity capacitance, C_x.

For analysis let us choose one of the many parallel receiving circuits. With reference to Fig. IX/3.4.3-1C it is clear that if V_i is the sine wave excitation voltage then for feedback

resistance and capacitance R_i and C_i, respectively, the amplifier gain can be derived as

$$V_o/V_i = (j\omega C_x R_i)/(1 + j\omega C_i R_i) \quad \text{(IX/3.4.3-1)}$$

This is possible because an ideal high amplifier circuit (e.g., op Amp) has infinite input impedance and very high gain. So, by ignoring any resistance from the switching circuit and stray capacitances, C_{s1} and C_{s2}, amplifier gain can be derived as given in Eq. IX/3.4.3-1.

With high-frequency excitation,

$$\omega C_i R_i \gg 1 \text{ so } V_o/V_i = \frac{C_x}{C_i} \quad \text{(IX/3.4.3-2)}$$

Generally, wire mesh technology suffers from an intrusive effect, which will be dealt with in the next section. This is applicable for both types.

3.4.4 INTRUSIVE EFFECT OF WIRE MESH SENSING

If one recalls the initial discussions on wire mesh it was mentioned that wire mesh measurement is intrusive in nature so it has an effect on measurement and flow characteristics. Such effects come from the sensor configuration, i.e., wire diameter, material, spatial resolution, etc. The intrusive effects are mainly on bubbles. There are two types of such effects. These were studied by researchers by comparing images with high-speed video cameras, etc. Major observations revealed that the sizes of bubbles more or less agree with other images, but there is fragmentation of bubbles in stagnant liquid. The results also showed that the repeatability on void fraction measurement showed some deviations and as a consequence typical uncertainty of measurement is around 5%. Therefore, it is a good technique for comparison purpose.

With this the discussions on wire mesh technology come to an end and we now investigate another important technique of EIT. Preliminary discussions on the EIT concept have already been discussed in Section 1.2.3, which may be read prior to this discussion on EIT.

3.4.5 ELECTRICAL IMPEDANCE METHOD (GENERAL: LOCAL MEASUREMENTS)

1. **Basics:** The electrical impedance type (EIT) basically operates on the fundamental principle that the electrical impedance of a multiphase/mixture is usually different from the impedance of each component. Some correlation between the phase/void fraction and the mixture impedance is possible if and only if the constituents have dissimilar electrical properties. It is known that gas has poor conductivity and low dielectric constant. On the other hand, liquids if not good conductors will at least assume a higher value of the dielectric constant. Oil has low conductivity while water is conductive and oil has dielectric much lower than water, so these properties can be exploited to measure the phase fraction.
2. **Method features:** In connection with void fraction measurements, for multiphase (especially in two-phase) flow research on the impedance technique has been studied for nearly 4 decades and good results have been found. Impedance sensors have proved to be very successful systems for measurement of time- and volume-averaged void fraction for identification of the flow pattern from its instantaneous output. Thus, in view of a few favorable features, the electrical impedance method has been widely used for void-fraction measurement in multiphase flow metering for quite some time. Instantaneous response, nonintrusive measurement, low cost, easier installation and implementation, easy mobility, and higher safety (due to no radiation) are a few features that immediately come to mind. However, it should be noted that the response characteristics of the electrical signal heavily depend upon the flow pattern and relative phase fractions. As electrical properties change with temperature, measurement is dependent on temperature. On account of noise due to the electromagnetic field around the sensor, the signal output is significantly affected by the presence of an

electromagnetic field, which can be minimized by using a suitable shield. Another issue worth mentioning is that there is no direct relation between the admittance of the mixture and the void fraction. For a single admittance value there can be different void fraction values, depending on the different flow patterns present. In view of differences in electrical conductivities and relative permittivities, between gas and liquid phases it is possible to develop the impedance method to find the void fraction in multiphase flow. Based on sensor height, the impedance sensor determines the percentage of both phases in a given volume and not strictly across a cross-sectional area. On account of the fringe field effect, the exact boundary is hardly possible to ascertain. By reducing the electrode height some nonlocal effects can be minimized but not the fringe field effect (it is better to use a large shield for stray capacitance) [36]. Depending on the operational frequency of the signal applied and the knowledge of the electrical properties of the fluids, the average dominating impedance of the two-phase mixture filling in the cross-section may be either resistive, capacitive, or both. As mentioned in Subsection 1.2.3.3, there are two other types: the resistive and the capacitive impedance probes. Configuration of each type has been covered in Subsection 1.2.3.3 which may be referenced. The elementary electrical model of the sensor and the measuring system that operates without electrolysis near the electrodes' surfaces can be compared to a parallel RC circuit [37]. The impedance type may consist of using capacitance and resistance in parallel, but if a component like water is present then at low frequencies there will basically be a short circuit effect. So, for taking capacitance into measurement it is preferred to use a high-frequency signal of around 80 MHz.

3. **Electrode type:** As indicated earlier, the relationship between void fraction and impedance depends very much on the flow regime. In order to minimize and circumvent the situation, various alternative probe designs have been applied and investigated. Several types are normally encountered:
   - *Coaxial:* Quasiuniform and very sensitive to void distribution and flow pattern;
   - Parallel flat plates;
   - Wire grid;
   - Wall flush-mounted circular arc;
   - Concave type;
   - Helical type;
   - Ring type.

The types listed above are generalized. In fact, there is some overlap between the types described above, e.g., in plate-type sensors, pairs of concave electrodes are arranged on the inner or outer walls of the pipe and measure the electrical impedance between them. There may be some minor variations in each of the categories, depending on the application. Selection of probe type is not always an easy task. There are different types of capacitance probes shown in Fig. IX/1.2.3-3B. Of these the helical type has a nonlinear response and poorer sensitivity and shield. On the other hand, the accuracy of the concave parallel sensors can be improved by having both electrodes of equal length to decrease the nonuniformity of the electric field between the two electrodes and eliminate the nonlinear response [36]. Concave and ring types are quite popular. As shown in Fig. IX/1.2.3-3B both ring type & concave sensor electrode covers the entire circumference, with small for a small gap to facilitate the installation of the sensor. As shown in Fig. IX/1.2.3-3A, there are full and half rings for conductivity sensors. Ring-type electrodes, covering the entire circumference, are convenient for measurements in pipes and columns of circular cross-section.

3.4.6 SOME RECENT DEVELOPMENTAL WORK IN ELECTRICAL IMPEDANCE MEASUREMENTS

In this section some of the developmental work towards EIT has been presented. The first is for horizontal line research, while the latter one is for vertical line research. Developments, from literature study has been presented here, for reader to

understand how EIT (not tomography) can be utilized for visualization of multiphase flow.

1. **New conductivity type probe:** In this method in place of two probes there is a third probe, which through numerical data analysis makes it possible to get better results. Typical electrode arrangements and measuring circuits have been presented in Fig. IX/3.4.6-1. In this method there are two steps for the measurements. In the first step, the flow pattern is identified using the conductance signal measured in all electrode pairs. Then, in the second step, the void fraction is estimated through the calibration curve for the flow pattern predetermined in the first step [38]. For further details the original article [38] may be referenced.

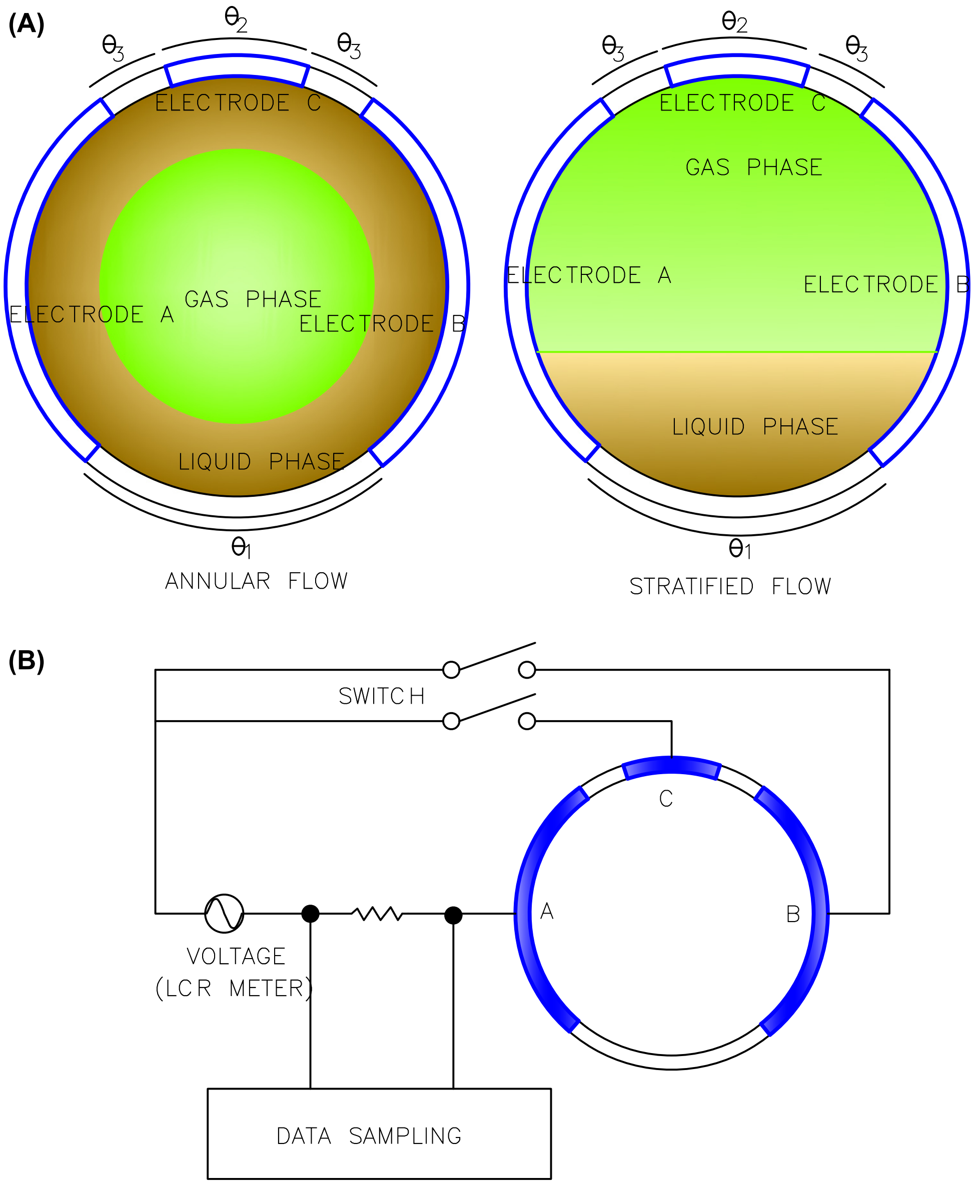


FIGURE IX/3.4.6-1 Three-probe conductance sensing. (A) Electrode arrangement for different flow. (B) Sensor measuring scheme. *Figures shown here are developed based on M. Seok Ko, B.A. Lee, W.Y. Won, Y.G. Lee, D.W. Jerng, S. Kim, An Improved Electrical-Conductance Sensor for Void-Fraction Measurement in a Horizontal Pipe, Science direct, Elsevier, 2015. http://www.sciencedirect.com/science/article/pii/S1738573315001680.*

2. **Void fraction visualization:** By now it is clear that the electrical impedance method can be used for local measurement, i.e., to find phase fractions and in conjunction with other instruments it can be used for interpreting multiphase flow. The electrical impedance method is very much in use in noninvasive, nonintrusion tomography and is popularly known as electrical impedance tomography (EIT). EIT has been discussed separately in this chapter. In this section short further discussions will be presented on quasilocal measurement by the electrical impedance method. From literature studies it has been found that such quasilocal measurement, in conjunction with various other instruments, is possible to obtain a visualization approach of multiphase flow. Electrical impedance type can detect local changes in electrical conductivity and permittivity, the technique is used to study the unsteady mixing or flow dynamics of mixtures. Using sequences of images obtained from a dual-plane EIT flow sensor, the local flow velocity of the dispersed phase(s) can be deduced based on *pixel-pixel* cross-correlation methods [39]. A short description is enumerated below in order to give an idea of the tomography approach. In this method a number of other instruments are used to get individual flow parameters.

Here an electromagnetic flow meter is used for continuous-phase velocity with input from EIT. "EIT technique with dual-plane sensors is used for local volume fraction distribution, local flow velocity and rate of the dispersed phases. The online measurement of local volume fraction distribution and profile of the dispersed phases is based on the average of volume fractions of individual pixels, which constitute the entire image. The three-phase flow mixture density (ρ^{FDM}) estimated from the gradiomanometer (FDM) is one of the three basic variables along with those measured by EIT and EMFM to enable the three phase measurement " [39]. The mean component volume fraction is determined using the correlation of EIT and FDM and applying the following mathematical formulae:

$$\overline{\alpha_o} = \frac{(\rho_w - \rho_g) - (\rho_w - \rho^{FDM})}{(\rho_o - \rho_g)} \quad \text{(IX/3.4.6-1)}$$

$$\overline{\alpha_g} = \overline{\alpha}^{EIT} - \overline{\alpha_o} \quad \text{(IX/3.4.6-2)}$$

$$\overline{\alpha_w} = 1 - \overline{\alpha}^{EIT} \quad \text{(IX/3.4.6-3)}$$

A typical schematic of the same has been presented in Fig. IX/3.4.6-2. For further reading consult the original document [39]. There are various effects such as fringe effect, stray capacitance effects double layer effects. These are discussed in Fig. IX/3.5.0-1.

With this the discussions on EIT, as well as wire mesh sensing, come to an end. Further details on electrical impedance tomography shall be dealt with under tomography in Section 3.6.0 of this chapter. Now let us look for another technology with a needle probe.

3.5.0 Needle Probe (Local Void Fraction)

A needle probe is one of the most useful tools in mapping the void fractions in multiphase/multi component flows. Significant differences of thermal conductivity, electrical conductivity, and optical properties are mainly exploited in needle probes to measure local void fraction and from there it is possible to map the void fraction distribution in a given area/volume in a conduit by moving the probe in different positions. Needle probes in different configurations can be used to measure the following:

- Local void fraction of phases;
- Local axial velocity in two-phase flow;
- Vector velocity of dispersed phase, etc.

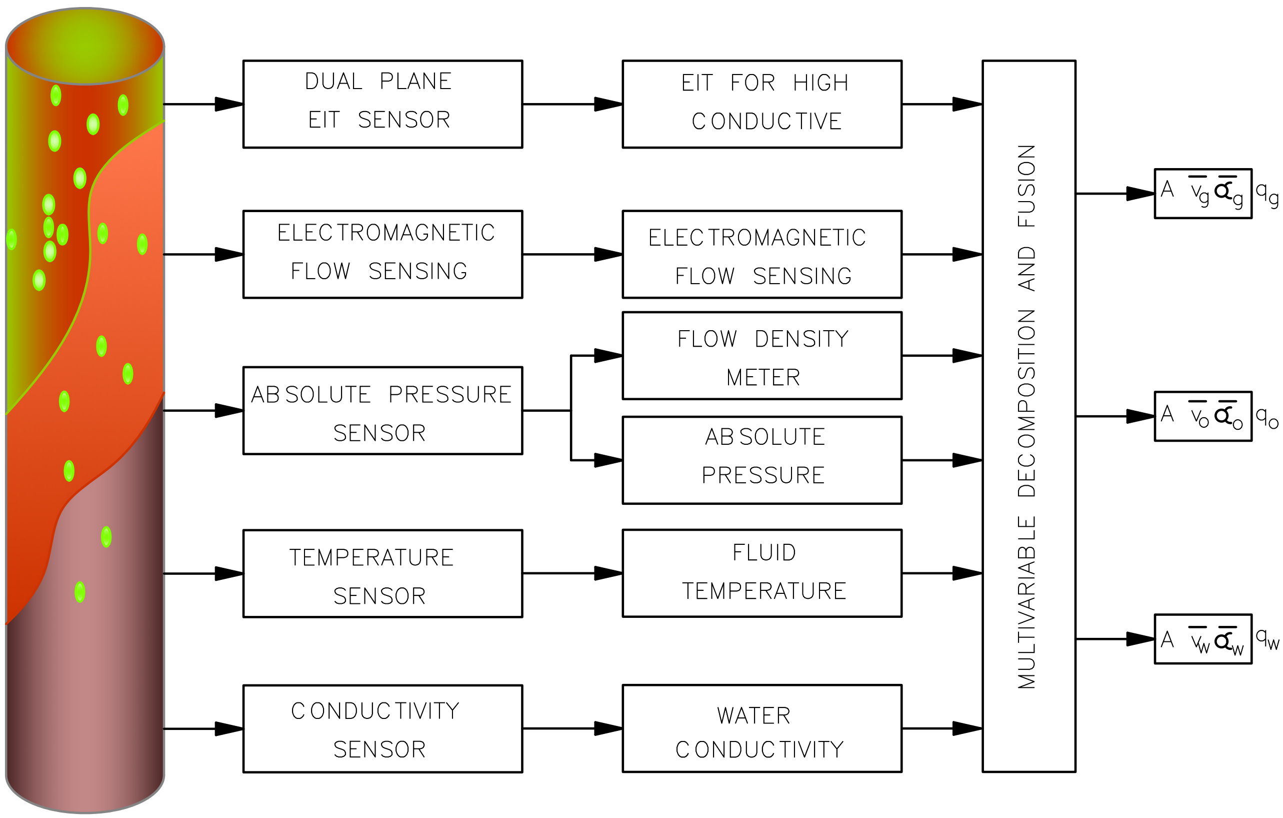


FIGURE IX/3.4.6-2 Multiphase flow visualization concept. *Figures shown here are developed based on M. Wang, J. Jia, Y. Faraj, Q. Wang, C. Xie, G. Oddie, K. Primrose, C. Qiu, A new visualisation and measurement technology for water continuous multiphase flows, Flow Measurement and Instrumentation, 46 (2015), Elsevier. http://ac.els-cdn.com/S095559861500076X/1-s2.0-S095559861500076X-main.pdf?_tid=49d52380-992f-11e6-b592-.*

Miscellaneous effects: A few following important effects are described here:

Fringe effect: This is a three-dimensional effect on area probes to induce error. In conduction probe suitable guard can be used and capacitive sizing is important to minimize the effect.

Stray capacitance effect: This represents the undesired capacitance that may be between cable and ground. These are unpredictable. The change of capacitance due to change in phase fraction is less the circuit design need to take care of this.

Double layer effect: This is rather less known effect and can be caused due to polarization i.e., local build up of opposite charges in excess number (capacitive sensing) to cause error. So, a suitable design technique should be adapted to build the system.

FIGURE IX/3.5.0-1 Miscellaneous effects.

It is seen quite often that these are used for comparison of results obtained from various other means, e.g., dual-plane EIT. If one recalls the discussions in Subsection 1.2.3.5 and described in Fig. IX/1.2.3-5 one would notice that there are basically three categories of needle probes used in day-to-day industrial applications. These basically are optical, thermal, and electrical. The principles of operation of these have been discussed already in Subsection 1.2.3.5. However, it is worth noting that in many cases a number of such categories are combined to get better results. There are conductivity and capacitance needle probes available, but in many cases these two are combined to develop an electrical impedance needle probe. Similarly, new improved needle probes are available where both electrical and thermal properties have been utilized for better measurements. As there is not much of a difference in the refractive index of organic liquid and gas (e.g., Boyer et al.) their use in multiphase flow, like that in oil and gas industries, is not recommended. However, optical needle probes find their applications in multiphase reactors. In this section brief discussions shall be presented on each of these types of needle probes in multiphase flow measurements. It is not that these probes cannot be utilized in isolation, but they find good applications in conjunction with other types of measurement technologies in multiphase flow measurement (MPFM). Signal processing is an important issue associated with needle probes, hence suitable care needs to be taken of this (Fig. IX/3.5.0-1).

3.5.1 OPTICAL TYPE NEEDLE PROBE

A typical working principle of an optical needle probe has been discussed in Subsection 1.2.3.5. Here a few other options have been discussed. One of the earliest and popular methods is visualization of multiphase/component flow. Identification of the flow regime by this technique is rather subjective and mainly suitable for *low-velocity* applications. This requires transparency in one of the phases and one viewing window. There are many options for this type of measurement.

1. **LDR type:** Light-detecting resistance (LDR) can be utilized for detecting the void fraction. This is very suitable for flow patterns during *liquid-liquid* flows in vertical and horizontal conduits. The interface may be smooth or wavy for separated flow patterns. One phase may be dispersed in the other phase as drops or bubbles. The probe response should also be sensitive to the proportion of the two fluids in the flow passage [40].
   - *Probe assembly:* A nonintrusive and noninvasive optical probe comprises a point semiconductor laser source, a light-dependent resistance (LDR) detector, and a processing circuit. The laser source and the LDR sensor are placed at diametrically opposite points to detect light transmitted by the laser source after it passes through a conduit containing multiphase fluid, as shown Fig. IX/3.5.1-1. The narrow laser beam passes through the two-phase medium before falling on the LDR. From the source to the sensor, the laser in its path passes through two different phases with interfaces formed by bubbles, drops, waves, etc. Each of these interfaces represents the characteristics of flow pattern causing different interactions like reflection, refraction, absorption, scattering, etc. Naturally, the amount of light reaching the LDR sensor is absolutely dependent on the fraction attenuated (depends on the absorption coefficient of the fluid) and scattered by the two-phase mixture. At the onset of droplets and wavy interface there will be scattering, which is dependent on the phase content and flow pattern. This is a good and simple system; only the liquids should be transparent. The optical probe system is installed on the transparent pipe by a U-shaped perspex block [40].

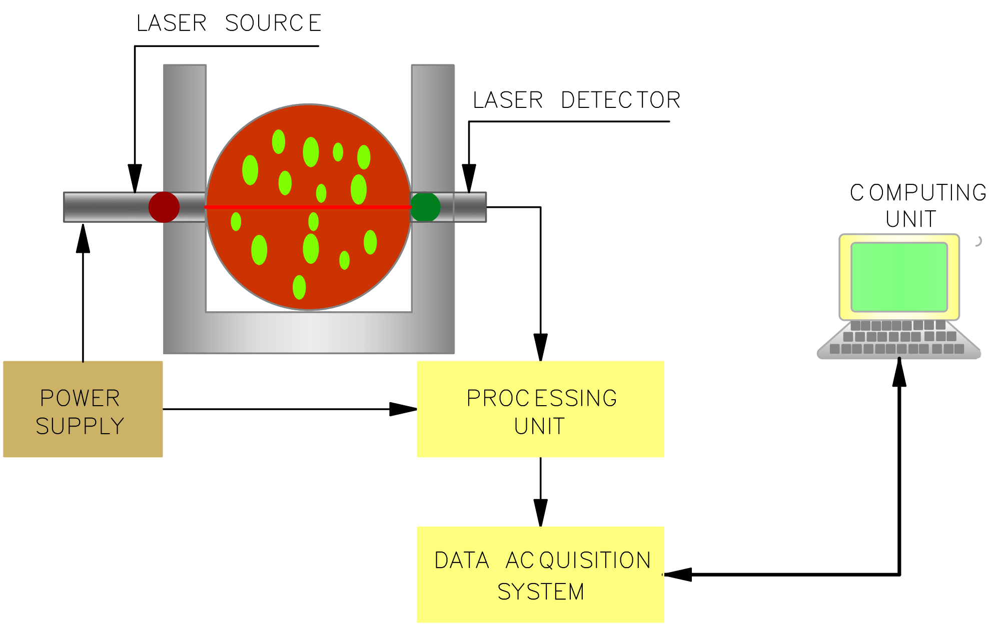


FIGURE IX/3.5.1-1 LDR type optical needle probe.

- *Processing circuit:* Based on the amount of light falling on the LDR, a variable resistance is generated depending on the intensity of light received at the LDR after being attenuated by the flowing fluid. Through the regulated power supply unit supplies constant DC source to the variable resistance of the LDR detector. The voltage across the resistance is the required output. The output from the LDR is amplified and processed by a processing unit, as shown in Fig. IX/3.5.1-1. Output is connected to the data acquisition system and computing unit to adjust the offset and other signal processing unit and presentation in a visualized manner in the display unit.

2. **Fiberoptic sensor:** Of the various noninvasive techniques, fiber-optical probes are very promising, because of their inherent advantages such as the following:
   - Harsh environment tolerance and strong electromagnetic interference immunity;
   - High temperature withstanding;
   - Immunity to chemical corrosion;
   - Small size and low power consumption;
   - Long-distance operation;
   - Multiplexing and distribution.

Also, improved optical and mechanical properties and lower cost of the components make it versatile. These also find their usage in multiphase flow. However, it may be somewhat more costly and unfamiliar to the end user.

As discussed in Subsection 1.2.3.5, basic measurement mode can be conceived as what is shown in Fig. IX/1.2.3-5A. Light sources used to support fiberoptical sensors produce light that is often dominated by either spontaneous or stimulated emissions. A combination of both types of emission is also used for certain classes of fiberoptical sensors. Fiberoptic sensors are mainly used in multiphase reactors.

3.5.2 THERMAL TYPE NEEDLE PROBE (COMBINED)

Electrical conductivity and capacitance probes can be used when there is a difference in electrical conductivity and permittivity between the components of multiphase flow. Similar is the case with optical probes, with low refractive index differences. However, temperature measurements are only possible when temperature *gradient* are encountered in the flow. These are used as two-phase flow measurements. Basic thermal type needle probes are an anemometer type thermal switch used to detect the presence of gas and liquid phase in multiphase flow to visualize the distribution, as discussed in Subsection 1.2.3.5. There are some improved versions of

thermal type probes available. In a true sense it is not a pure thermal probe but a combinational probe where both thermal as well as electrical properties have been utilized. In addition to anemometer type, needle probes with integrated microthermocouples are also used. Among many other difficulties with these was the slow time of response for the system.

Preamble: A new combined temperature and conductivity needle probe measuring system, has fast response. This is able to handle grounded or direct sheathed thermocouple wires electrically joined to the protective sheath, as well as open thermocouples [41]. This combined probe also measures local conductivity in the test volume with a high time of resolution (10,000 samples/s). It has been found that these probes can face extreme conditions, like pressure up to 160 bar and temperature up to 300°C (water/steam) [42]. The probe combination can measure the following:

Averaged local gas fractions;

Flow velocities;

Bubble number and bubble sizes.

The probe tip, thereby, consists of a miniature sheath thermocouple, which allows the *synchronous* measurement of temperature and conductivity at the same measuring point in the medium, i.e., thermal and conductivity probe from Helmholtz Zentrum Dresden.

The probe: There are different constructive embodiments of the probe. The basic probe consists of a coaxial structure of three stainless steel electrodes which are isolated from each other by two aluminum oxide ceramic tubes. The central (probe tip) is a direct sheath thermocouple as shown in Fig. IX/3.5.2-1. Apart from the thermocouple there are three other electrodes:

The reference electrode: the outer probe connected to the ground;

The shield electrode: middle one, connected to the transmittance amplifier;

Measuring electrode: Thermocouple sheath; also connected to the transmittance amplifier.

The thermocouple measures the temperature, while the measurement of the local instantaneous electrical conductivity of the surrounding fluid gives the local void fraction.

Measurement scheme: The measurement scheme consists of several amplifiers and a signal processing unit as detailed in Fig. IX/3.5.2-1. A bipolar signal is applied to the central measuring electrode. Depending on the presence of fluid in contact with the electrode either current will flow to the ground or it will stop, i.e., if the fluid in contact is the fluid of certain conductivity (say water), there will be current flow, otherwise if it is covered by a gas bubble the current will be interrupted. In order to prevent a short circuit through thin liquid films still covering the isolating ceramics, a central shielding electrode is used. The system excitation signals are generated through direct a digital synthesizer (DDS 1&2—with a common reference clock to synchronize). To make the shield active, one DDS1 signal is applied to the shield as well as the positive end of the transimpedance amplifier. Conductivity is therefore measured by connecting the measuring electrode to the other end of transmittance amplifier. The output signal of the transimpedance amplifier is thereby superimposed by a permanent signal, which has to be removed [42] and for this differential amplifier, which has another input from DDS2 (same frequency by controllable phase to match the time delay), has been used in series with a transmittance amplifier. High gain instrument amplifier is used for the low-voltage signal generated by the thermocouple. For better measurement accuracies, a cold junction compensation unit and low-pass filters are used. In the digital control part for regulating DDSs, microcontrollers are often deployed. The system is normally connected with computer/computing circuits. RS 232/422 and ethernet can be used for external communication. Here embedded electronic micro-controller play very vital role in measurement control and computation.

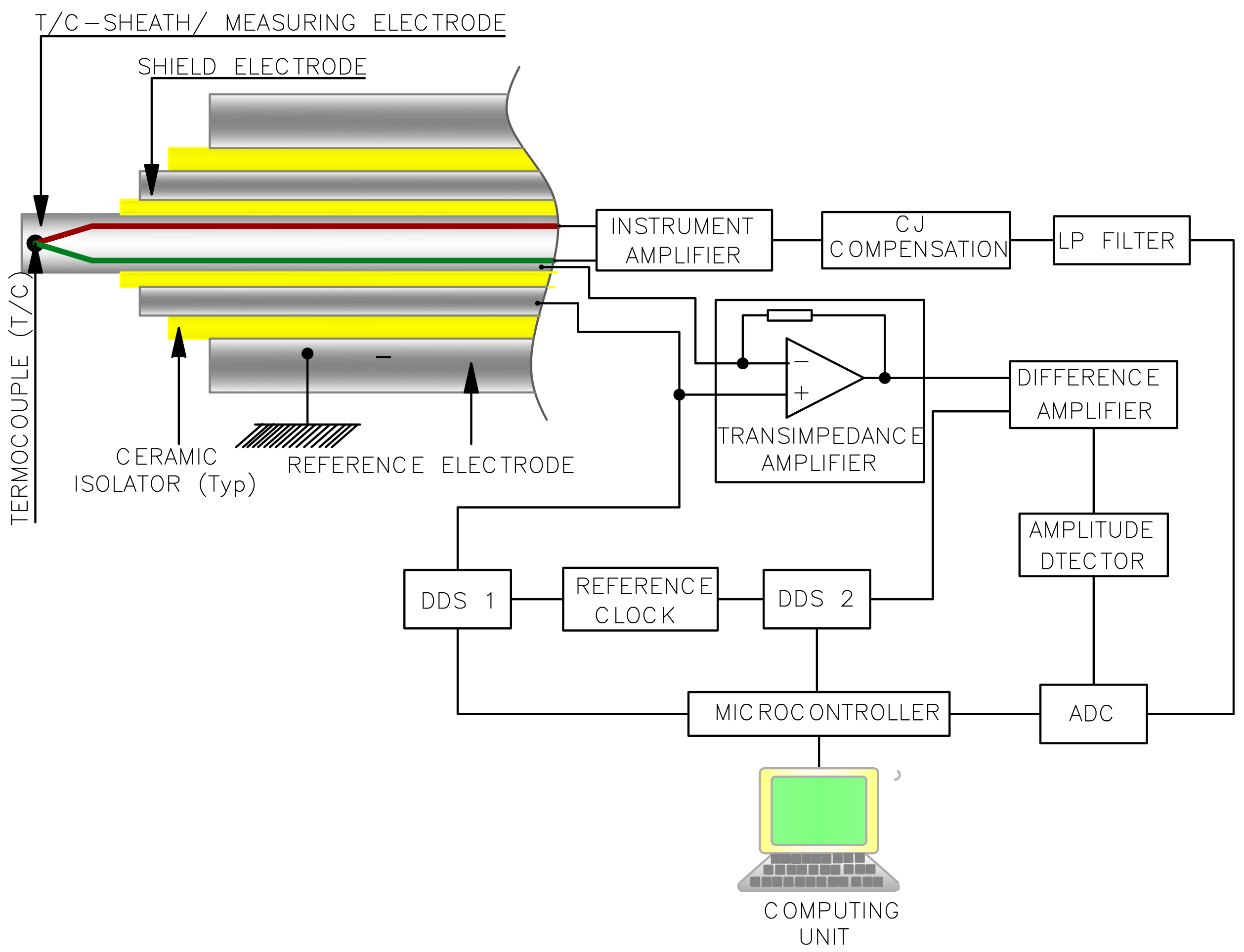


FIGURE IX/3.5.2-1 Combined thermal and electrical needle probe. *ADC*, analog−digital converter; *CJ*, cold junction; *DDS*, direct digital synthesizer; *LP*, low pass.

3.5.3 ELECTRICAL TYPE NEEDLE PROBE (COMBINED)

Electrical needle probes can be conductivity type as described in Subsection 1.2.3.5, or they can be capacitance type, and/or a combination of both, i.e., complex admittance type. Electrical probes can be single-, dual-, or four-sensor arrays, etc. These probes are often used for comparing results obtained from EITs. In this section, brief discussions on each of them shall be covered.

1. **Conductivity probe application:** Here some typical applications of conductivity sensors have been described from study of literature (experiment at the University of Huddersfield, UK).

- *Dual sensor:* Typical sensors used are depicted in Fig. IX/3.5.3-1A [43]. These are two conductivity probes with a gap (0.5 mm gap in width). The probe consists of two PTFE-coated stainless steel needles of outer diameter 0.15 mm, with the PTFE removed at each needle tip to allow electrical contact with the multiphase flow [43]. The needles are held in place by glue in a ceramic guide and are positioned such that one needle tip, known as the front sensor, is placed an axial distance s upstream of the second needle tip, known as the rear sensor (1.5 mm gap). The local void fraction is a dimensionless, time-averaged

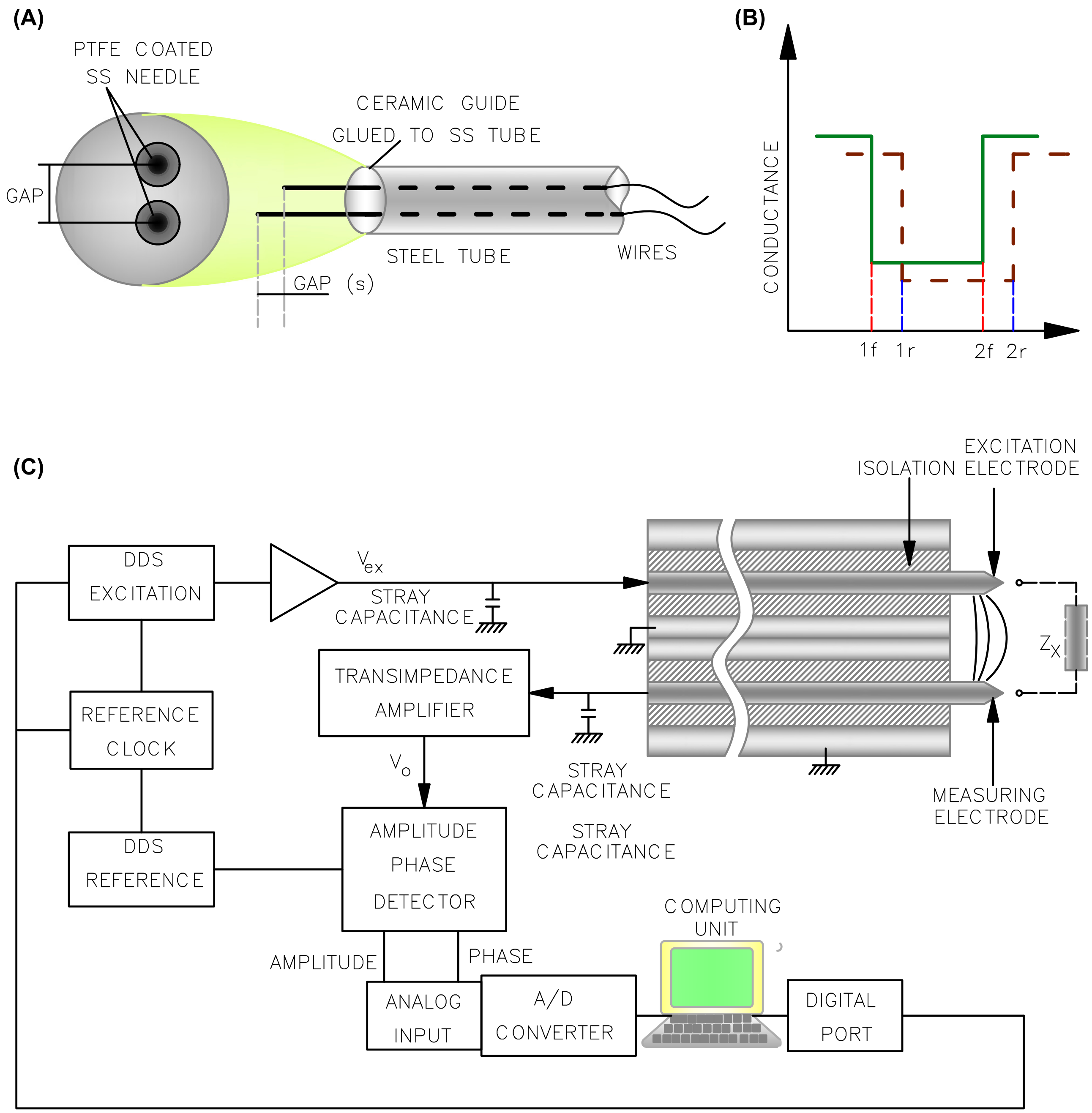


FIGURE IX/3.5.3-1 Electrical needle probe types. (A) Dual conductivity probe. (B) Probe conductance. (C) Combined electrical needle probe. *A/D*, analog-to-digital; *DDS*, direct digital synthesizer. *(A and B) Developed based on G.P. Lucas, X. Zhao, Large Probe Arrays for Measuring Mean and Time Dependent Local Oil Volume Fraction and Local Oil Velocity Component Distributions in Inclined Oil-in-water Flows, Elsevier, 2013. http://www.sciencedirect.com/science/article/pii/S0955598613000393.*

quantity that can be calculated statistically over a sampling time. In contact with two-phase medium when the surface of an oil droplet first contacts a sensor, there will then be a sharp drop in the measured conductance, but this is regained when the droplet has passed over the sensor. These are shown in Fig. IX/3.5.3-1B. Let this occur with a front sensor at times t_{1f} and t_{2f}, respectively. Let the same for the rear

sensor be denoted by t_{1r} and t_{2r}, respectively. Over the sampling period T, the number of oil droplets that strike both the front and rear sensor is N. Thus, from Fig. IX/3.5.3-1B for first encounter for *n*-th droplet, one can define:

$$\delta t_{1n} = t_{1r,n} - t_{1f,n} \text{ and } \delta t_{2n} = t_{2r,n} - t_{2f,n} \quad \text{(IX/3.5.2-1)}$$

If s is the distance for axial difference then the average velocity could be calculated as:

One can estimate the mean local axial velocity easily utilizing a statistical mean from the acquired data.

$$u_o = \frac{2s}{N}\sum_{1}^{N}\frac{1}{(\delta t_{1n} + \delta t_{2n})} \quad \text{(IX/3.5.2-2)}$$

Since the gap t_{2f} and t_{1f} is the time period tip in contact with oil, so the oil volume void fraction is:

$$\alpha = \frac{1}{T}\sum_{1}^{N}(t_{2f,n} - t_{1f,n}) \quad \text{(IX/3.5.2-3)}$$

In the same experiment, a four-sensor array was also used.

- *Four-sensor array:* With the help of a four-sensor array it is possible to get the velocity vector also. An individual four-sensor probe is used to measure the mean local oil volume fraction α and the mean local oil droplet velocity vector averaged over a sampling period T. A four-sensor probe can be used to measure the velocity vectors also [43].

2. **Capacitance needle probe:** Conductivity measurement is possible if one of the components is conductive in nature, i.e., one component has minimum conductivity. A capacitance probe based on permittivity change is also used as an electrical needle probe. Normally multineedle probes are used. There could be a multiple number of needle sensors, e.g., five needles to form four local capacitances which are sampled at a very fast rate to detect the changes in permittivity. There can be one common excitation electrode to which the AC (sinusoidal) signal is sent and measurement is carried out in the other four measuring electrodes. These are connected to a transimpedance amplifier. The output of the transimpedance amplifier is demodulated to get DC voltage proportional to the change of permittivity, i.e., instantaneous capacitance between the excitation electrode and each measuring electrode. As in previous cases, processing of these signals and data available from sampling can provide the local multiphase flow parameters like phase fractions, local axial velocity, etc.
3. **Combined electrical needle probe (complex probe):** Here, instead of only conductivity or capacitance sensing, complex impedance sensing is done.
   - *Preamble:* Pure conductivity- or capacitance-based needle probes have limitations regarding the range of substances they are able to measure. Electrical conductivity and capacitance probes can be used when there is a difference in electrical conductivity and permittivity between the components of multiphase flow. As indicated earlier, there will be similar difficulty with an optical probe when there is a low difference of refractive index. A thermal probe could be the solution if there is a temperature gradient but is utilized almost exclusively in two-phase flow measurements. Therefore, there is a lack of measuring techniques for three- or multiphase flows encountered in oil extraction, chemical reactors, and petrochemical industries. An electrical probe combining conductivity and capacitance measurements could provide better solutions. This means that in electrical measurement instead of measuring in one axis (conductivity—real or capacitance—imaginary) measurement could be carried out in a complex plane of admittances. A needle probe with impedance could provide a better solution.
   - *Probe and measurement:* The probe has double coaxial geometry, as shown in Fig. IX/3.5.3-1C. The probe assembly consists of one excitation electrode and one

measuring electrode in stainless steel construction. Each probe has coaxially one grounded reference probe, which is isolated from the excitation or measuring probe by a suitable isolator as shown. The objective of measurement is to determine the complex impedance based on the amplitude and phase measurement of the sine wave signal at a fixed frequency (200 KHz to 1 Mhz). The excitation voltage *Vex* is supplied to the excitation electrode by means of a coaxial cable. The measuring electrode is connected to a transimpedance amplifier by means of a coaxial cable. The output voltage of the transimpedance amplifier is directly proportional to the current I flowing from the excitation to the reference electrode $V_o = I \cdot Z_f$, where Z_f is the feedback impedance (refer to Fig. IX/3.5.2-1 for details of the transimpedance amplifier). Since the unknown admittance of the fluid Z_x is grounded by the operational amplifier's virtual ground, the current I is obtained by dividing voltage V_i with impedance hence for Z_f feedback impedance of transmittance amplifier:

$$V_o = I \cdot Z_f \text{ and } I = V_i/Z_x$$

or

$$V_o/V_i = Z_f/Z_x = Y_x/Y_f. \qquad \text{(IX/3.5.2-4)}$$

where it is noted that the excitation voltage generated by DDS is V_{ex} may be (slightly) different than V_i due to stray capacitance. The complex impedance Z_x, measured by the probe, is inversely proportional to the relative permittivity ε_r as:

$$Z_x = (1/(j\omega \cdot \varepsilon_r \cdot \varepsilon_0 \cdot K_g). \qquad \text{(IX/3.5.2-5)}$$

where ε_0 permittivity at vacuum 8.85 pF/m; $\omega = 2\pi f$, K_g denotes probe geometric factor.

- *Processing unit:* As shown in Fig. IX/3.5.3-1C, the processing unit is similar to that shown in Fig. IX/3.5.2-1. The probe is excited by direct digital synthesizer (DDS)1 and output is measured by a transimpedance amplifier. There is one amplitude and phase detector unit which basically acts like a demodulator. The output from the transimpedance amplifier is fed to an amplitude and phase detector and the signal is demodulated. Amplitude and phase detectors are powered through DDS2, which has the common clock with DDS1. DDSs are controlled by microcontroller of the computing unit.

With this the discussions on needle probe come to an end and we start discussions on various types of tomography techniques.

3.6.0 Tomography Techniques

In order to identify the internal flow characteristics of multiphase flows, one can use either invasive measurement techniques or noninvasive methods. The difficulty with invasive methods is that they can alter the internal flow of a multiphase system causing interference with realistic process measurements. Nonintrusive acquisition of local measurements of process parameters like temperature, concentration, or volume fractions in multiphase flows is often a challenge. In many cases, instead of the desired local measurements, only integral measurements, for instance along lines, can be obtained. This is the point when process tomography comes into play [44]. Tomography is an imaging technique, to produce cross-sectional details of an object from its line integrals of projections. On account of the larger variations in density and to achieve finer resolution, the design and operation of computerized tomography (CT) machines for process/industrial and scientific applications is more complex when compared with medical systems for which the techniques was initiated. In tomography, one of the issues is the reconstruction of images from the acquired data to visualize time-resolved flow structures in 2D/3D. Such reconstruction of images from acquired data is done mathematically with the help of suitable algorithms which form an integral part of the tomography system. Depending on the measurement task, a variety of optical, electrical conductance, electrical

capacitance, X-ray, gamma ray, and other tomography can be used. Each of these systems vary significantly on the following aspects:

- Spatial resolution;
- Temporal resolution;
- Suitability for particular applications;
- Availability in the market;
- Cost factor;
- Familiarity/experience of personnel;
- A few other pertinent issues.

The discussions start with generalized discussions on the tomography technique.

3.6.1 GENERAL TOMOGRAPHY PROCESS

There are a number of techniques for tomography, i.e., X-ray, CT, electrical impedance (ERT, ECT) tomography, gamma ray tomography, US tomography, etc. The application of tomography in process industries is not only in oil extraction but other plants as well, including upstream and downstream of oil and gas industries such as fluidized catalytic cracking and multiphase pipe flow [3]. Tomography often decides the calibration basis for multiphase flow meters. "In addition, the notion of tomometry as a means of nondestructive measurement technique will be introduced as tomometry relies upon cross sectional metering of process parameters utilizing multiple measurements where fulltomograms are not required" [45]. With the advancement of sensor technologies, versatile signal processing and recovery electronics make it possible to measure more and more parameters with better accuracy. Added to this there have been a number of development in data acquisition and computing networks with advanced reconstruction algorithms making tomography an important measuring tool. The following are general steps for tomography:

- Around the test section there shall be a number of sensors which measure the required parameter through periodic scanning of the test section;
- The associated electronics process the signals sequentially for presentation to the data acquisition system as inputs;
- The processed data are acquired by a data acquisition system, which is basically a computerized system. With the help of software these process data are interpreted;
- Advanced software-based reconstruction algorithm.

An image reconstruction algorithm is a real challenge in the process of interpreting tomographic data to create images of the distribution, which gives rise to the set of measurements. This involves good mathematical interpretation issues (problems) and a good amount of developmental work for algorithms. The basic steps have been depicted in Fig. IX 3.6.1-1. For improved process utilization, and process yields, process controls and cost-effective solution tomography finds more uses in petroleum industries, especially for oil and gas exploration. With more and more use these are now available with high-quality assurance, and better environmental and safety protections.

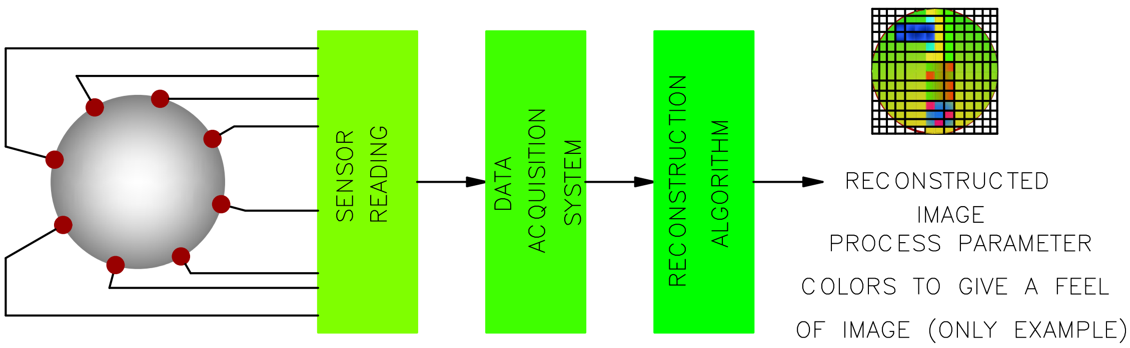


FIGURE IX/3.6.1-1 Tomography principles.

The aim of design should be to develop a system as a simple one but with higher reliability to provide the required information and data. With an advanced tomographic system industry tomographic measurement systems are often preferred with a few views for permanently installed gauges as a measurement scheme—as long as it provides sufficient information. Tomography is used for both reservoir characterization and to search for it. A variety of new technologies have made it possible to reach a 60% recovery factor [44]. Tomography can be categorized in main three categories:

- Nuclear-based imaging technique using ionizing radiations such as X-ray, gamma ray, neutron/positron radiation. These are often referred to as "hard field" as the measurement sensitivity to measurement parameters is independent of component distribution;
- Nuclear-based imaging: without using ionizing radiation such as nuclear magnetic resonance;
- Non-nuclear-based imaging techniques such as electrical impedance tomography, US tomography, optical tomography, and microwave tomography.

Various ways and means of radiation from source and detection methods, including relative movement of source/detector with respect to the process, have been depicted in Fig. I/3.4.3.2-1. As shown, there may be single or multiple source and detector combinations with and without scanning, i.e., instantaneous type.

Now, it is time to look into the details of the various tomography techniques.

3.6.2 X-RAY TOMOGRAPHY: X-RAY CT

Like the gamma ray radiation technique already discussed, in this technique also, the radiation beam traveling through the heterogeneous medium undergoes attenuation before being detected at the detector. The absorption gives a measure/indication of the line integral of local density along the beam path.

1. **Process:** The components have different radiation absorption characteristics, therefore, the image of phase is obtained by reconstruction of a set of projections at the different orientations generated. This is achieved by rotation source and detection around the pipe or by use of two (multiple) sources and detectors, as detailed in Fig. I/3.4.3.2-1. In a digital X-ray system there are image intensifiers and charge-coupled device (CCD) as described in Fig. IX/3.6.2-2, cameras read the images. The movement of this may be achieved through a suitable motor, e.g., a stepper motor, duly controlled by the data acquisition system (DAS). As indicated before, detected data are processed and sent to the DAS, which is connected to a computer (computing unit). On account of the automated process, i.e., computer-assisted tomographic process, it is referred to as computer-assisted tomography (CAT) or computed tomography (CT), i.e., X-ray CT. Tungsten or molybdenum are X-ray sources that generate low-energy photons. On account of mechanical movement of the source and detector (not applicable for multiple sources and detectors) the temporal resolution is not very good but the spatial resolution is excellent. The basic process of X-ray tomography has been depicted in Fig. IX/3.6.2-1, along with some typical possible images.
2. **Phase distributions:** These are spatial and temporal:
   - Cross-sectional;
   - Time series.
3. **Mixing effects:** The mixing effects are observed in the following manners:
   - Cross-sectional;
   - Time and space distribution;
   - Interface roughness;
   - Waves.
4. **Results:** Typical results from X-rays are as follows (a few only):
   - Tomographs;
   - Side and top projection views;
   - Mean holdup traces;
   - Sliced sectional view;
   - 3D view of the flow;
   - Y-axis phase distribution;

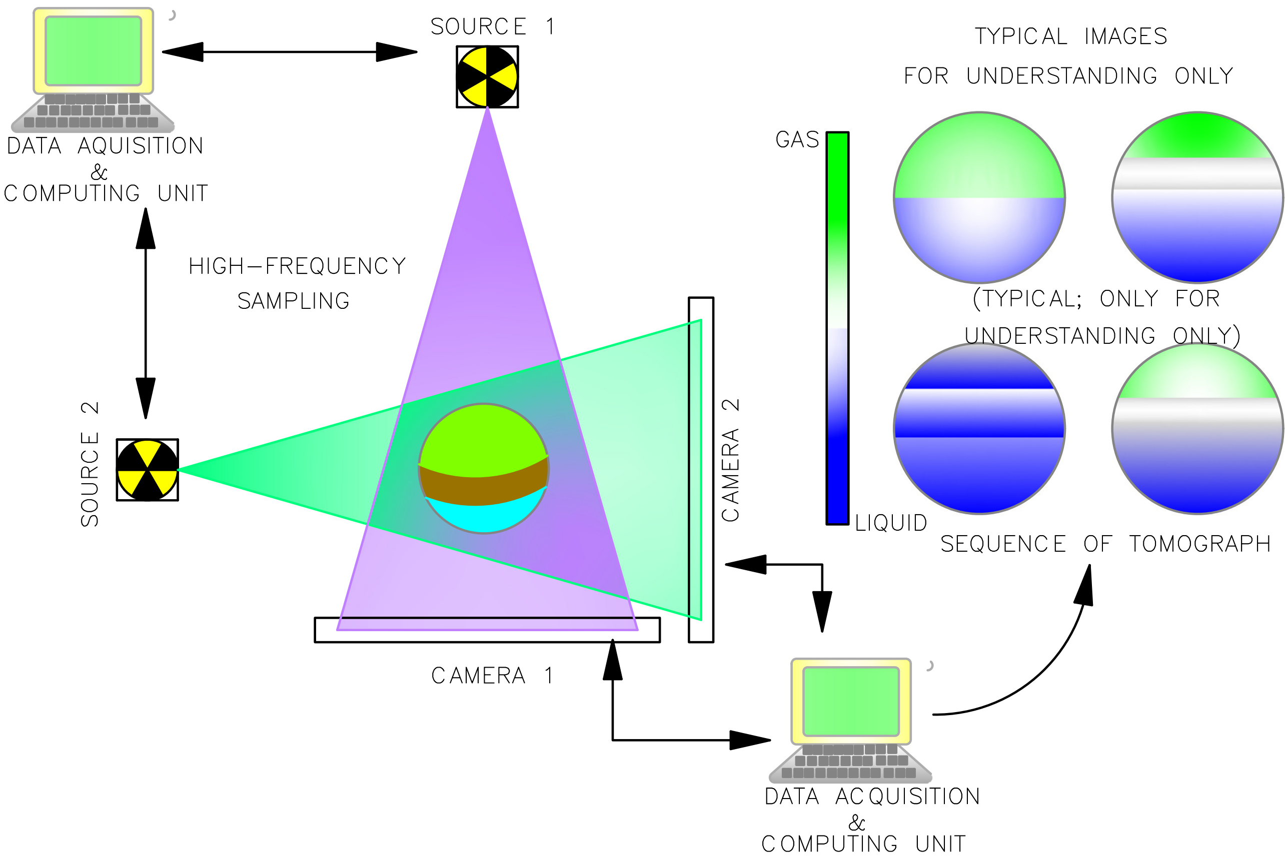


FIGURE IX/3.6.2-1 X-ray tomography (CT).

CCD & CMOS: *Charge coupled device (CCD) and Complementary metal oxide semiconductor (CMOS) are used as sensor in digital camera/imaging devices to convert optical energy into electrons or electrical energy. CMOS is a semiconductor device which can perform other duties as well only it is explained in this perspective.*

FIGURE IX/3.6.2-2 CCD and CMOS for digital imaging.

- Phase transport along slug or wave;
- Others.

5. **Statistical parameters:** The following are statistical parameters that are obtainable:
   - Wave height;
   - Frequency;
   - Slug body length and distribution;
   - Three phase flow extension.

For X-ray spectroscopy process any standard book on X-ray spectroscopy may be referenced. To limit the book size it is beyond the scope of the book only relevant could be presented. We now concentrate on another nuclear ionizing tomography technology of gamma rays.

3.6.3 GAMMA RAY TOMOGRAPHY

The basic principles of the gamma ray detection technique with single energy or multiple energy gamma rays have already been discussed at length in Sections 1.2.3, 2.1.0, and 3.3.1. Now we concentrate on gamma ray tomography.

1. **Preamble:** When rotating systems are used, the results will yield time-averaged, not instantaneous, phase distribution images with time

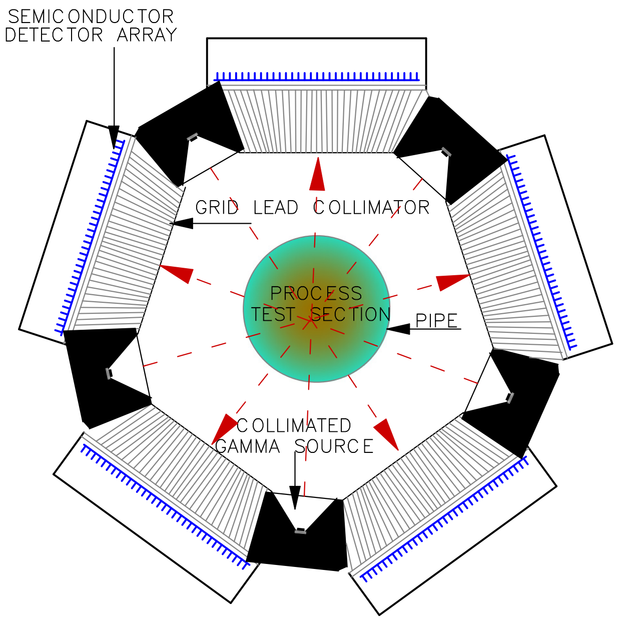


FIGURE IX/3.6.3-1 Gamma ray tomography.

resolution of such systems is limited to a few images per second. Here the description has been provided with multiple sources and detector systems, which would allow the study of dynamically changing phase distributions. However, such solutions are still comparatively complex and cost-intensive [11].

2. **Description:** An industrial high-speed gamma-ray tomography system consisting of a number of gamma sources (refer to Subsection 3.3.1.2—Am-241 radioisotopes more common) with principal associated gamma-ray energy and equal number of detector modules placed opposite to the source. As shown in Fig. IX/3.6.3-1, the detector system consists of a grid lead collimator and an array of semiconductor detectors. Detectors are connected to suitable readout/processing electronics, which in turn is connected to the data acquisition system. A computer is associated for reconstruction of images, like X-ray tomography. The area of each detector and thickness in design are very important for the performance of the system. The area of each detector is around $10 \times 10\ mm^2$ which was found to provide the best compromise between spatial resolution and ray-sum measurement error. All detectors used are ~2 mm thick in order to provide nearly 100% stopping efficiency—quoted data from [45]. There are a number of error sources in measurements, such as photon scattering from the same source or from other sources due to Compton scattering effect. Also, there will be errors from reconstruction pixel density. In order to minimize the errors from scattering, a highly collimated source and heavily collimated gird detector as shown can be used. In order to have better temporal resolution, a set of multiple source and detectors are used in place of a single source detector set with rotation. In oil exploration applications it has been found that high-speed gamma ray tomography is extensively used as multiphase flow loop reference imaging and for down-hole measurement [44].

There is another kind of nuclear-based tomography—the neutron type. Neutrons have some advantages in terms of their attenuation in matter in comparison to photons.

3.6.4 NEUTRON/POSITRON TOMOGRAPHY

Neutron imaging may not be very common with medical applications, but for engineering process testing it is often used. In principle, neutron imaging works in the same way as X-ray radiography, with a few important physical differences in the sense that the neutron imaging can provide certain *information* that would be impossible with X-ray radiation. The basic principle of operation of this is generally similar to that of X-ray. In the case of neutron radiation, in addition to a radiation source, neutrons need an evacuated collimator through which the neutrons are propelled before they hit the test object. The detector behind the sample provides a two-dimensional image of the radiation. It is possible to develop a tomograph/tomogram. In the case of positron emission tomography (PET) positron-emitting radionuclides are used with an external detector. Normally, PET has longer temporal resolution and may not be a good choice for fast-changing flow investigation.

X-ray radiation is a form of electromagnetic radiation, while neutron radiation is neutral and has more penetrating power. Also in X-ray reaction probability is more. Lead can be used as a shield for X-rays but not for neutron radiation. However, neutron and X-ray radiography of the same object often produce complementary information.

3.6.5 ELECTRICAL IMPEDANCE TOMOGRAPHY

Electrical impedance tomography (EIT) is an important type of process tomography. As the name implies electrical impedance is exploited to get the interaction of electricity with the process. Hence it is often referred to as electrical tomography. Complex electrical impedance consists of resistance, inductance, and capacitance, and varying physical parameters associated with them are conductivity, permeability, and permittivity, respectively. Depending on the modality of exploitation of the parameter, these could be any of the following:

- Electrical resistance tomography (ERT), when conductivity distribution is exploited;
- Electrical capacitance tomography (ECT), when permittivity distribution is exploited;
- Electrical magnetic tomography (EMT), when permeability distribution is exploited.

It is clear from the above that EIT should never be used as a synonym for ERT or ECT. While ECT is nonintrusive and generally noninvasive (for metal vessels or pipes, ECT may be invasive) but ERT may be invasive but nonintrusive. An image is obtained when an electric field is applied between two electrodes and measuring the resulting sensor responses. Although in basic theory of measurement of these are similar to those discussed in Subsection 1.2.3.3, yet final output types as well as measuring processes are different—as will be clear from the subsequent discussions. A complete dataset is obtained by successively activating each electrode and measuring the responses of all remaining electrodes. EIT normally is quite fast, and hence has good temporal resolution. It is also low-cost and safe (from radiation). EIT offers moderate spatial resolution of the resultant image and the measured electrical signals are not a linear function of phase fractions and flow configuration. Also, the electrical field cannot be confined between the source and detectors, and is referred to as soft-field tomography. Now it is time to investigate each of the available types of electrical tomography.

1. **ERT:** The imaging technique ERT can capture the internal structure of a two-phase flow within an opaque pipe or vessel. As already mentioned, the basic principle of measurement is the difference in the conductivity of the constituent phases within a multiphase flow domain. ERT is used for measuring the behavior of mixing, flow, and separation where the reactants or products have different conductivity, for instance crystallization. ERT is used when the materials are conductive, for instance: water, acids, bases, and ionics. Therefore, of the several ERT applications, study of multiphase flow is an important application. ERT produces cross-sectional images showing the distribution of electrical conductivity of the process pipe/vessel from the measurements taken at the boundary of the pipe/vessel. In ERT the process flow is interrogated by an array of electrodes (typically 16 electrodes) at the periphery of the pipe wall. An electrical current is injected through a pair of electrodes and the voltage is measured through the *remaining* electrodes in pair, according to the predefined protocol. The next injection of current is started with another pair and voltage measurement as stated above is continued. This process is repeated until all independent measurements are over. For 16 electrodes there will be 104 possible independent measurements. A typical electrode arrangement and orientation have been depicted in Fig. IX/3.6.5-1A. By placing two sets of this at distance apart, it is

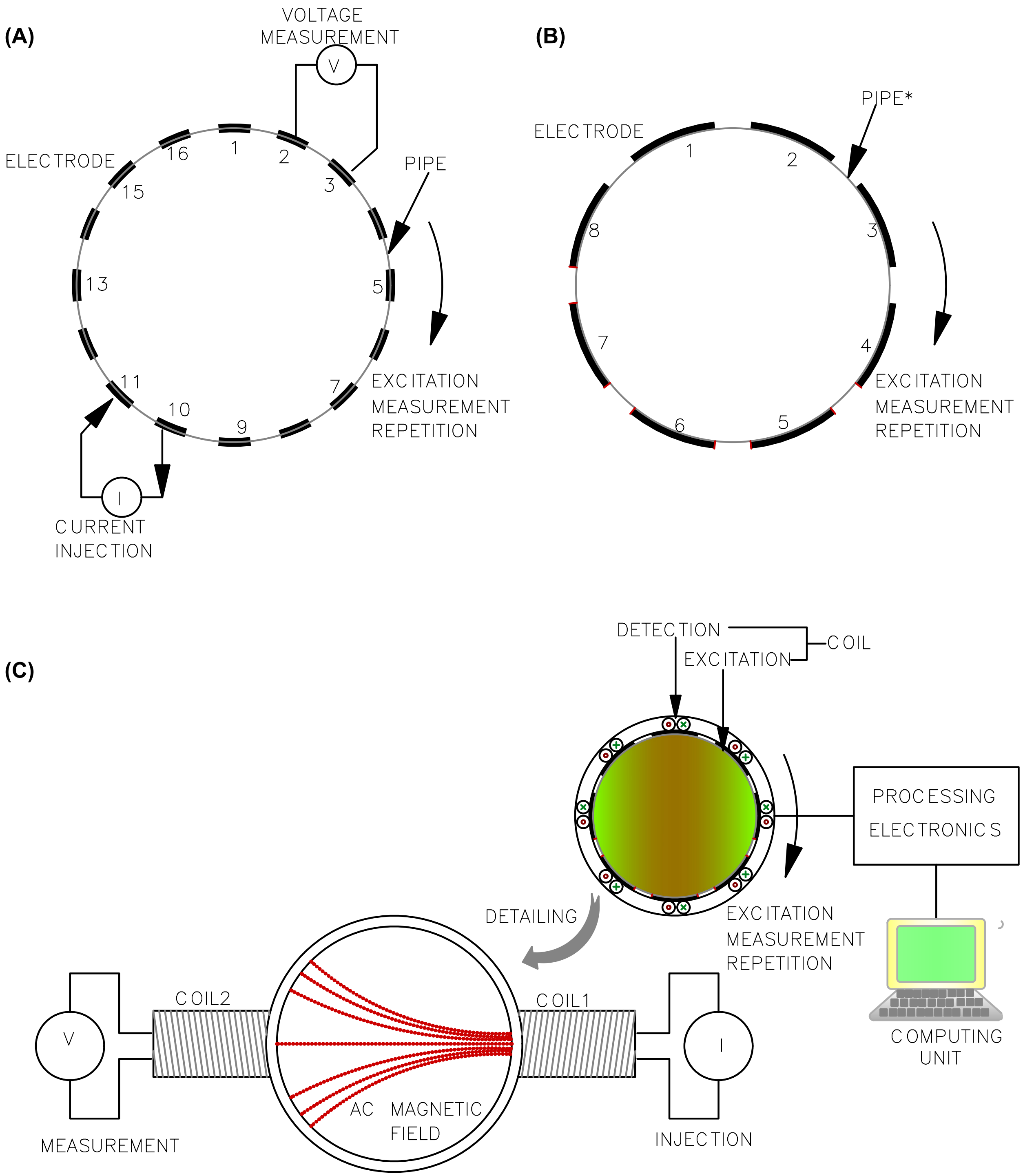


FIGURE IX/3.6.5-1 Electrical impedance tomography. (A) ERT electrode orientation. (B) ECT electrode orientation. *Pipe: nonmetallic electrode outside (noninvasive) for metallic pipe electrode inside invasive. (C) EMT measurement scheme.

possible to get velocity profile also utilizing co relation method discussed earlier. The basic design issues include but are not limited to the following:

- *Electrode spacing:* Electrodes shall be equally spaced;
- *Electrode materials:* Electrodes are normally made up of SS, Br, Ag, etc. with conductivity more than process fluid;
- *Electrode connection:* Electrodes are connected to DAS via coaxial or other special cable;
- In ERT, gas volume fraction profiles in an annulus flow can be measured.

2. **ECT:** is another tomography technique, utilizing electrical properties, for measuring and displaying the concentration distribution of a mixture of two insulating (dielectric) fluids, such as oil, gas, plastic, and some minerals, inside a vessel/pipe.
   - *Features and types:* ECTs normally are deployed when the bulk material in question does not have conductivity. For interpretation of the ECT image, colors have suitable significance, e.g., in an ECT image red stands for high dielectric value, for instance oil, and blue stands for low dielectric value, e.g., gas. Depending on pipe materials ECT can be completely noninvasive or invasive. As stated earlier, in the case of a metal pipe, the electrodes will be inside the pipe and it will be intrusive, otherwise ECT will be noninvasive, i.e., electrodes surrounding the test section will be outside the pipe/vessel.
   - *Principles and applications:* Basically, in ECT the changes in electrical capacitance between all possible combinations of electrodes are measured. This happens when the dielectric material is poured inside the pipe or vessel introduced. Interelectrode capacitance change is caused due to differences in the permittivity of materials (gas—low permittivity; liquid—higher permittivity) in the mixture, i.e., from these measurements, the permittivity distribution of the mixture (related to the concentration of one of the fluids) can be deduced. The basic idea is to surround the vessel with a set of electrodes of metallic plates to take capacitance measurements between each unique pair of electrodes. Vessels/pipes of any cross-section can be imaged by a set of electrodes surrounding the test section, as shown in Fig. IX/3.6.5-1B. The resolution of ECT images is relatively low, but they can be captured at high speeds. As indicated in previous discussions it is possible to measure the velocity profile with the help of a cross-correlation method by placing two sets of measurements along the pipe length. Apart from two-phase flow applications in oil and gas fields, it finds applications in fluidized beds, flow rate measurement in pneumatic conveying systems, and flame and combustion imaging.
3. **EMT:** The operation of EMT is very similar to the other electrical tomography methods. Here an AC magnetic field is applied to the process in question and changes in the field contour on account of the presence various materials in the mixture.
   - *Measurement steps and objectives:* In EMT, the test section is excited with an AC magnetic field. Changes in the field contours result from the presence of the mixture in the test section.
   - Measurement of the field values by the sensors at the boundary surrounding the test space.
   - Data acquisition and interpretation of sensor data.
   - Image reconstruction with suitable mathematical algorithms. This involves converting

the measurements back into an image of the original material distribution.

- *Principles of operation:* As shown in Fig. IX/3.6.5-1C, the measurement involves twin coils. One coil is for excitation and the other for detection. Sinusoidal current is passed through the exciting coil so that there will be a magnetic field generated in the object area. With a presumed background condition of relative permeability in the test section, due to AC magnetic field there will be induced voltage generated across the detection coil which can be measured to detect the changes in permeability condition due to the passage or flow of the mixture. The measured voltage will be interpreted, corresponding to a background or empty space measurement [46]. On account of the introduction of mixture in the test space the spatial distribution of the magnetic field, i.e., the mutual coupling between the coils, is altered.
- *Description:* As shown in Fig. IX/3.6.5-1C, the system consists of three main subsystems, i.e., sensor array, processing electronics including data acquisition system, and computer (computing unit). As shown in the blown-up part of the figure, the sensor array consists of an outer magnetic confinement shield, excitation coils, detection coils, current driver for each excitation coil, and buffers/amplifiers for detection coils (not shown). Since the measurement is based on a change in permeability, any electrically conductive or ferromagnetic objects within the test section or nearby space would disturb the measurement. Like any other tomography reconstruction, a software algorithm is very important for the system also, so that an image of the material distribution can be properly understood and interpreted.

With this the discussion on EIT comes to an end and we now look into magnetic resonance imaging.

3.6.6 ULTRASOUND TOMOGRAPHY

Like electrical impedance tomography, in ultrasonic tomography the changes in the acoustic impedance properties due to multiphase flow are detected. Gas–liquid flow exhibits a marked acoustic impedance difference between the gas and liquid interfaces [11]. In ultrasound tomography multiple ultrasonic transducers are mounted around the pipe, as shown in Fig. IX/1.2.4-1. US tomography has already been discussed in Subsection 1.2.4.2 and so is not repeated here.

3.6.7 OPTICAL TOMOGRAPHY

Optical tomography makes use of low-energy electromagnetic radiation in visible, infrared, or ultraviolet wavelength range in the electromagnetic wave spectrum. Like other tomographic systems, acquired data are suitably interpreted in DAS and, with the help of an image reconstruction algorithm, images are prepared in CT mode.

3.6.8 MAGNETIC RESONANCE IMAGING

Magnetic resonance imaging uses nuclear magnetic resonance of hydrogen nuclei in conjunction with radio frequency and magnetic gradient pulses to map the test section (Mantle and Sederman, 2003). As stated above, it acts on hydrogen nuclei and so fundamentally, in MRI the concentration of hydrogen atoms is detected. By this method it is possible to determine the density of nuclei and also the velocity in flow. Typical petroleum multiphase flows containing gas, oil, and water have hydrogen atoms in all these components.

With reference to Fig. IX/3.6.8-1, when placed in a magnetic field the nucleus of the hydrogen

Precession: Magnetic Resonance (MR) happens as a result of *intrinsic magnetic moment* of nucleus (proton and Neutron). In many atoms such as O16/ C(12) magnetic moment of proton and neutron offset each other. On the contrary H atom has the strongest MR response (as H is present in gas/oil /water this is utilized in MPFM). Thus when subject to static magnetic field, later it exerts a *torque* on the axis of the spinning to move the axis perpendicular to the direction of force around the axis of magnetic field. This motion is known as ***Larmor Precession***. The *Larmor frequency* of this precession around the direction of the background magnetic field B_0 is determined by Gyromagnetic ratio γ and is given by $f_0 = \frac{\gamma}{2\pi} \cdot |\overline{\boldsymbol{B0}}|$

FIGURE IX/3.6.8-1 Larmor precession.

atom (proton) will always align with the applied magnetic field and processes will be active. When it is irradiated with radio waves of the same frequency, the protons resonate (as a reaction to the RF signal). The protons absorb and re-emit the radio energy of the same frequency. The emitted signal (*echo*) is proportional to the **number** of protons. Therefore, it is also called echo-planar imaging. The technique is relatively costly and discussed at length further in the following section.

With this the brief discussion on tomography techniques comes to an end. We now investigate available MRI-based industrial flow meters.

3.7.0 Magnetic Resonance Multiphase Flow Meter

The magnetic resonance imaging principle discussed in the above subsection, has been applied to develop a complete multiphase flow meter. This newer technology has been developed by Krohne. A brief discussion has been presented on the same (based on documents from Krohne: Courtesy: ***Krohne***).

3.7.1 BACKGROUND THEORY FOR MR RESONANCE MEASUREMENT

The basic physical phenomenon behind the measurement has been briefly explained here. As stated earlier, for H (two) alignments are possible, i.e., alignment at a certain angle with (or against) applied magnetic field. There will also be precession movement because of superimposition of external field on magnetic moment of proton (around the direction of external field). This phenomenon creates a net magnetization which is time-dependent. The orientation of the macroscopic magnetization, M, can be modified by applying radio-frequency pulses with the appropriate intensity, duration, and frequency. Changes in the orientation or intensity of the macroscopic magnetization can be detected as a small voltage in an appropriate RF coil as shown in Fig. IX/3.7.0-1B.

An RF pulse is created with the intensity and duration such that the magnetization vector, M, is tilted along the x-axis by 90 degrees (from the z-orientation to the x−y plane). This pulse is called a P90 pulse. By applying a P180 pulse at, e.g., $t = \tau$, all protons are flipped along the y-axis by

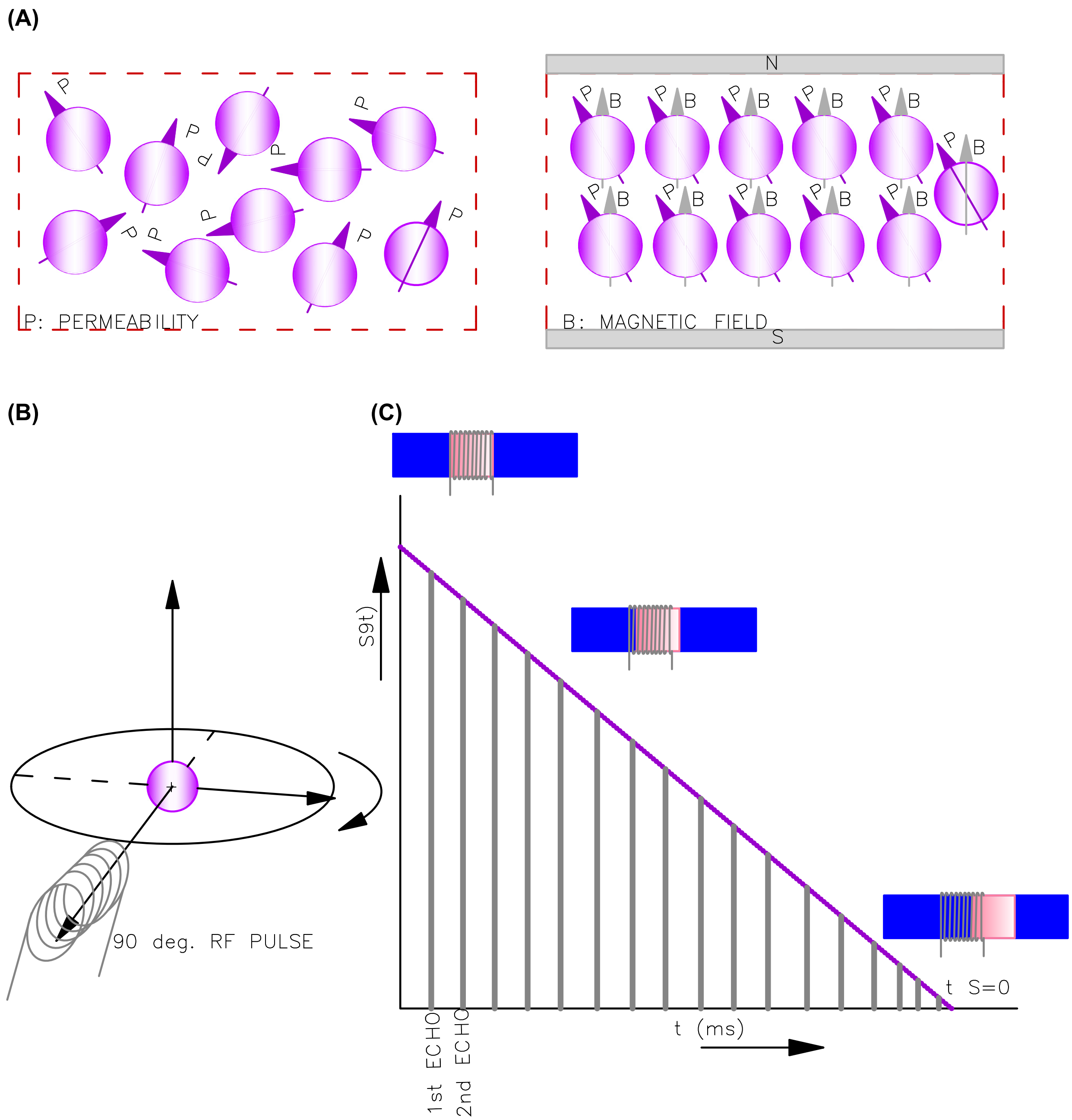


FIGURE IX/3.7.0-1 Magnetic resonance type MPFM. (A) Alignment with magnetic field. (B) Resonance with RF pulses. (C) Velocity measurement. *Developed completely from documents from Krohne. Courtesy: Krohne.*

180 degrees. As a result, there will be a gap (difference in movement) between the slower-moving protons and the faster-moving protons placed behind. With the individual resonance frequency remaining unchanged, all protons start to rephase, leading to an echo at $t = 2\tau$. This is referred to as Hahn echo. Hahn echoes can be created multiple times by repeatedly applying P180 pulses. This pulse sequence is called the CPMG pulse sequence. Besides CPMG, a variety of RF pulse sequences have been developed for measuring T1 or T2. By varying the timing of these pulse sequences, the measurement can be optimized to the expected MR response of the flowing fluids [47].

3.7.2 MEASUREMENT BY MAGNETIC RESONANCE PRINCIPLES

In line with multiphase flow metering principles, phase fraction (λ) and velocity of travel are measured to calculate volumetric flow rates (q). In the meter there will be pre magnetization stage, where water and oil attend max. and min. of their respective magnetization. It will be noticed there will be difference in magnetization of water and oil. For this the signal for two different magnetization lengths for oil and water to evaluate the ratio and from there the fraction of oil and water can be derived. From factory calibration $S_{100\%L}$, liquid phase fraction λ_L is measured by $\lambda_L \cdot S_{100\%L}$. So, phase fraction gas is inferred by $\lambda_G = 1 - \lambda_L$. Fluid velocity is determined by the convective decay method, excited protons leave the coil due to flow measure of the decrease in amplitude of the echoes $v = L_c \cdot t_{s=0}$, as shown in Fig. IX/3.7.0-1C i.e. The flow velocity is measured by analyzing the signal attenuation as function of time (referred to as convective decay method). Rf signals are applied in discrete way in gaps of milliseconds (manipulative) to measure the decay due flow. This helps in calculating the velocity discussed above. For further details Refs. [48,49] may be referenced. External and internal views of M Phase 5000 of Krohne (Courtesy: Krohne Messtechnik GmbH; permission: e-mail dated October 16, 2017) have been depicted at the end of the chapter.

3.7.3 METER PARTS

The meter consists of the following measurement sections and components:

- Premagnetization section;
- Motor to vary premagnetization length;
- Main magnet with RF coil;
- Electronics housing in flame-proof boxes.

We now look into another kind of multiphase flow meter type.

3.8.0 Sampling Type Multiphase Flow Meter

During the discussions in Subsection 3.4.2.3 of Chapter I and Subsection 1.3.1.3 of this chapter, the sampling type of measurement has been discussed. A multiphase flow meter utilizing a similar method is discussed here. This is known as the VIS multiphase flow meter of ABB. Here VIS stands or "Vega Isokinetic Sampling" of TEA Sistemi's Vega meter [50]. "The methodology used by VIS starts with an extremely sophisticated sampling system, implemented by means of specially designed and patented devices…" [51]. This is a proprietary device naturally description is based on the product literature. Now let us look into the details of this system. This meter is basically a wet gas meter as it operates mainly in GVF >80% up to nearly 100%.

3.8.1 PRINCIPLES OF OPERATION

In multiphase flow very complex fluid dynamics are involved, and proper sampling is very important to get the representative sample. The methodology used by VIS starts with an extremely sophisticated patented isokinetic sampling. Isokinetic sampling consists of the withdrawal of a sample of the three-phase flow in such a way that the sample taken is perfectly representative of the entire stream [51]. In this method "careful management of differences in pressure between the interior of the sample probe inserted into the main duct and the duct itself ensure the conditions of equivelocity that are essential to fully representative sampling" [51]. In this meter another important issue is separation. After sampling, the meter performs the separation process with the help of high-efficiency gas liquid separation. The separated liquid and gas are measured by conventional instruments, such as pressure, temperature, and DP transmitters, as shown in Fig. IX/3.8.0-1. As shown in this figure

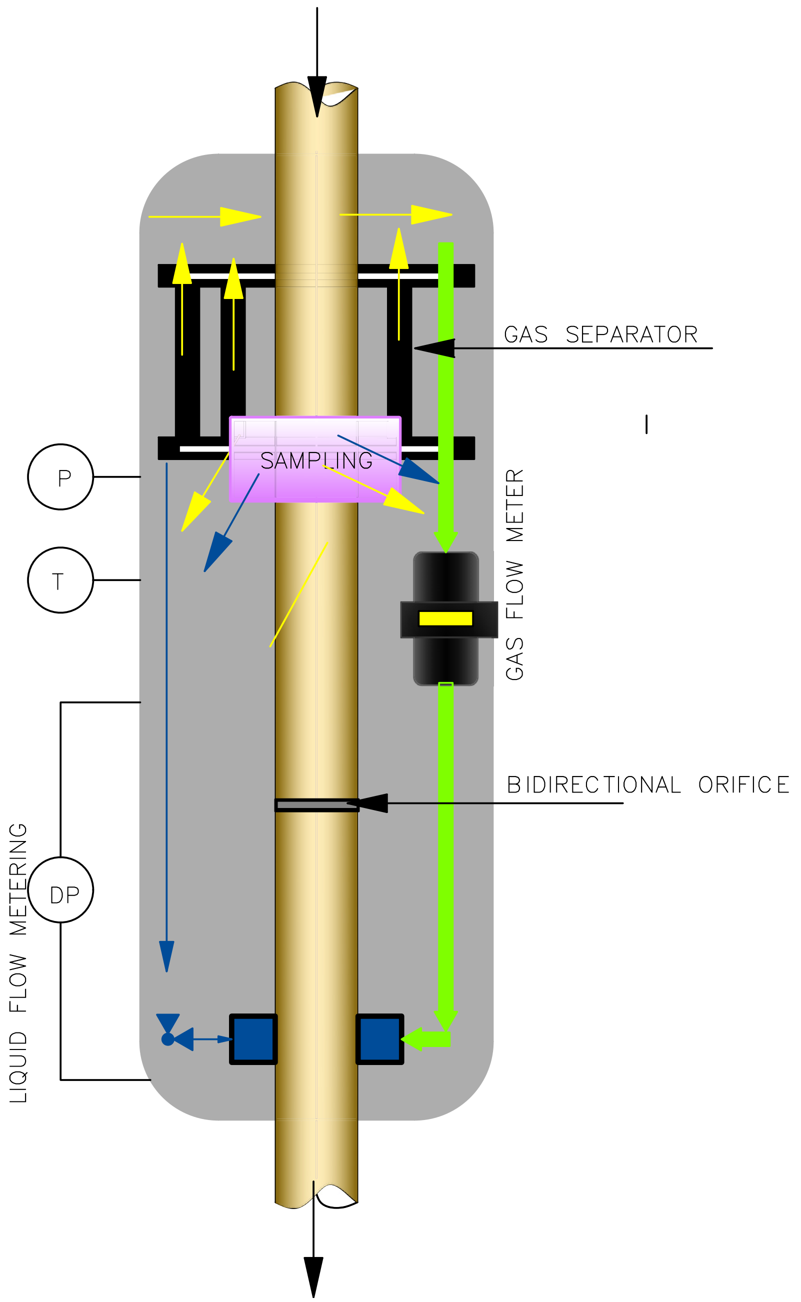


FIGURE IX/3.8.0-1 Sampling type multiphase meter. *Developed based on an idea from N. Bonavita, G. Ciarlo, ABB VIS Multiphase Flow Meter Un nuovo misuratore multifase "γ-free" per il monitoraggio e l'ottimizzazione della produzione nell'Oil and Gas, ABB Measurement Products, mcT Petrolchimico, November 2014, Internet document. http://www.aisisa.it/wp-content/uploads/2014/12/VIS_mcT_Petrolchimico_Rev1.pdf. Courtesy: ABB Limited.*

that sample only comes to the meter through the sampler. Then at gas separator gas is separated as shown light (yellow) arrow and liquid in dark (blue) arrow. There are separate gas meter an liquid meter (DP) as shown.

All such data are transmitted to a dedicated computing unit/PC station, which uses proprietary software for presentation of data in the form of flow rates of the individual phases. It is possible to get standard hardwired output or communication through a fieldbus, such as Profibus or Canbus. The meter is suitable for GVF $>$ 80%. By its nature, VIS provides maximum performance precisely, in extremely high GVF.

3.8.2 ISOKINETIC SAMPLING

The following are basic regulations followed for isokinetic sampling in an ABB VIS meter:

1. Sampling is done in the pipe at a place where gas and liquid are well mixed and velocity profiles are uniform.
2. The liquid volume fraction in the sample is the same as in the main stream.
3. Isokinetic sampling requires that the ratio between the sampling flow rate and the overall flow rate be the ***same*** as the ratio between the sampling probe cross-section and the pipe cross-section (at the sampling location) [50].
4. No field calibration is necessary and there are no empirical relations.

With this the discussions on the VIS meter and on multiphase flow metering technologies come to an end. In the following section discussions on miscellaneous issue for multiphase metering shall be covered, including selection criteria.

4.0.0 MULTIPHASE FLOW METERING —MISCELLANEOUS TECHNICAL ISSUES

In the above discussions, various technical issues related to fluid dynamics, terms with explanations and implications, and various technologies for measurements have been discussed. In this section brief discussions on a few other issues shall be covered to make the discussions on multiphase flow measurement complete. During the above discussions it has been shown that there are many types of instruments and instrument technologies for measurement. Also, there are different measuring types and parameters. From a user's point of view it is extremely important to know how to select the most suitable instrument for a particular application. Therefore, let the discussions start with meter selection.

4.1.0 Multiphase Flow Meter Selection Issues

The wide range of instruments and measurement technologies discussed above are designed to offer optimum performance in different fluids at different operating conditions. Naturally, when it is used in different conditions the same performance cannot be guaranteed, in fact it may not perform at all! Therefore, it is important to understand the merits and limitations inherent to each style of instrument and the operating conditions for which it is meant. The performance requirement of two-phase flow will be different from a typical three-phase metering system. Also, the operating conditions (e.g., GVF value) of wet gas measurement and the water-in-liquid ratio will be different. In the reactor studies context this measurement is complicated by the fact that during the transient period, the fluid becomes a nonhomogeneous mixture of liquid water and steam at (or very near) saturation [36]. It is needless to emphasize, that the MOC of the meter is extremely important so that it can withstand the harsh condition(s) it has to face in the field.

4.1.1 GENERAL REQUIREMENTS AND EXTERNAL CONDITIONS FOR METER SELECTION

1. **Operating conditions:** Ideally an instrument meant for flow measurement should be able to withstand and respond immediately but consistently to changes in fluid velocity, even if there is a fluid hammer due to a pressure surge (to suddenly stop or change the flow direction of fluid motion). Turbulent or pulsating flow may cause flow-registering errors and suitable considerations should be given for this. Apart from these operating pressure and temperature conditions, environmental conditions are also very important for meter selection. Changes in viscosity and temperature also affect meter performance. Excess temperature may be a cause of changes to the internal dimensions. Therefore, due consideration for these is warranted.
2. **Flow regime:** From the above discussions, it is clear that depending on pressure and temperature ranges, there will be different flow regimes. There are different flow regime demands for different responses. Unless the selected meter is capable of spanning all the pipe section of interest to detect average values of the measured quantity, the output could be misleading [36].

3. **Cavitation:** This phenomenon in two-phase flow is not uncommon and the meter should be sized and installed in a suitable way so that this is avoided.
4. **MOC:** The MOC for a flow meter, especially those in contact with the fluid, has direct bearing on meter performance, stability, and longevity. For special and corrosive applications, suitable MOC need to be arrived at. Meters are available with a wide range of materials, such as: CS, SS316, Hastelloy, tantalum, Monel, nickel, and titanium. In addition to these there are thermoplastic materials. Noninvasive flow application problems are less.
5. **Mechanical issues:** A number of mechanical issues listed below are also important considerations:
   - Pipe size;
   - Connection type;
   - Pressure (and temperature) rating of flange;
   - Upstream and downstream straight length (as applicable);
   - Requirement of any flow conditioner;
   - Necessary accessories;
   - *Installation:* horizontal/vertical/inclined;
   - Smaller footprint and weight are a requirements for offshore application on account of space restrictions and weight control.
6. **Maintenance need:** On account of dirt/solid particles, flow meters with moving parts obviously have more maintenance requirements than with those without moving parts. Also, meters with bearings have maintenance needs. For meters like DP meters there is an issue of the impulse line getting plugged. Meters using radioactive sources also have safety and maintenance issues to be considered.

4.1.2 SENSING SPECIFIC REQUIREMENTS

1. **Performance criteria:** In certain situations where flow meters are used to give an indication of the rate at which a liquid or gas is moving through a pipeline, high accuracy may not be crucial [36]. However, for custody transfer issues, i.e., where pricing/dispensing is involved or batching, sampling, and flow meter accuracy (refer to Chapter I for types of accuracy) are definitely an important factor in meter selection. Meter repeatability and response time are also important performance criteria.
2. **Calibration:** Meter calibration, as necessary, should be as simple as possible. Some meters, such as VIS, do not require field calibration. The calibrations are carried out at a temperature different from field conditions so it is better that calibration is as independent as possible from the temperature difference between the two conditions discussed.
3. **Conformance to local regulatory requirements.**
4. **Data acquisition system:** As seen, many of the multiphase flow meters require a huge quantum of data collection and handling so a good data acquisition system with suitable software should be chosen. Open platform software has advantages in this regard. Another important issue is system interface especially for software based systems. Fieldbus (discussed at length in Appendix VII) systems has inherent advantage.
5. **Bidirectional operation capability:** Some applications, such as in batch reactors, demand bidirectional flow capability, so that should be kept in mind.
6. **Sensor issues:** There are some sensing methods, such as wire mesh sensing, where the measurement type is intrusive. In such a situation care should be taken to ensure it does not cause flow disturbance. Also, while selecting a sensor it is important to note and take necessary steps so that the sensor signal processing is not too complex.

4.2.0 Multiphase Flow Meter Specification Issues

As the MPFM system covers a wide range of technologies and instruments, it is not possible to create a specification sheet. However, the following points could be taken into account for specifying MPFM systems.

4.2.1 PERFORMANCE SPECIFICATION

For any measurement, especially for MPFM performance, specification is of immense importance. Based on performance requirements often selection of MPFMs, as well as appropriate technologies for specific application, is arrived at. Standardized performance specifications will help users compare MPFMs proposed from different manufacturers for specific applications [1].

Apart from measurement uncertainty actually performance should cover broadly the following:

1. Measurement accuracy in suitable scale for comparison (AR/FSD);
2. Repeatability and reproducibility;
3. Sensitivity and resolution;
4. Reliability and stability of measurement;
5. Response time;
6. Influencing factor;
7. Measuring span;
8. Limiting conditions (as applicable);
9. Operating condition and limits of operation.

Such specification should include all the components and parts of the system, including primary devices such as sensors and transmitters. Since most of the measuring technologies involve intelligent measurement systems including DAS and computer performance of software and communication and control capabilities (of microcontrollers) along with updating capabilities are also important.

4.2.2 TECHNICAL DESCRIPTION

As already stated it is not possible to specify the meter type on account of the vast application area and vast combination of measuring types and technologies and associated complexities. The basic functional requirements can however be specified. As part of the specification for common understanding the following are of importance:

1. Overview of measurement scheme with suitable block schematic;
2. Description of overall measurement scheme and its objective;
3. Detailed description of all subsystems/components and devices, including sensors, transmitters, software, computers, to name a few;

TABLE IX/4.2.2-1 Input and Output Data for Specification (With Suitable Applicable Units)

Input to be Specified	Output Expected
Density per phase (kg/m^2)	Phase volume flow rate (m^3/h*)
Viscosity per phase (m.Pa)	Phase accumulated volume (m^3*)
Fluid (water) conductivity (μS/cm)	Pressure (bar)
Fluid permittivity (F/m)	Temperature (°C)
Linear attenuation coefficient (L/m)	Phase density (kg/m^3)
Mass attenuation coefficient (m^2/kg)	WLR (%)
Ambient condition temperature (°C)	GVF (%)

**Depending on application other lower unit are also used.*

4. Basic specification (with functional details) components/instruments/sensors;
5. Outlined specification (functional details) of measurements ranges/limit, etc.;
6. Description of configuration, parameters, and required input, such as fluid properties, operating conditions, site limitations, and requirements [1].

Some of the I/Os of the meter are as given in Table IX/4.2.2-1.

4.2.3 OUTPUT SPECIFICATION REQUIREMENTS

The following are the general minimum expected output from a three-phase MPFM:

1. Gas, oil, and water gas volume and/or mass flow rates;
2. For wet gas, gas/liquid volume and/or mass flow rates;
3. Phase fractions and/or WLR/GVF;
4. Density measured (as applicable);
5. Operating pressure and temperature conditions.

Additionally, a few other data are also provided by the metering systems.

5.0.0 MULTIPHASE FLOW METERING—INSTALLATION AND COMMISSIONING ISSUES

Field installations mean physical/mechanical installation, piping, as well as electrical connection, including communication network set up along with necessary protections. With a number of types of meters for metering technology, as well as varying site conditions, it is difficult to provide a detailed installation of metering systems like conventional single-phase meters discussed in previous chapters. Post installation comes the commissioning procedure. However, some guidelines have been established.

5.1.0 Brief Multiphase Installation Discussions

In this section brief discussions on installation guidelines and requirements shall be covered.

5.1.1 INSTALLATION GUIDELINES

The following points need to be considered for installations:

1. **Manufacturer's recommendations:** To follow the manufacturer's installation recommendations (as far as possible), i.e., prior to starting the installation it is necessary to get the manufacturer's installation drawing;
2. **Limits:** Due consideration must be given to the limits for the meter specified by the manufacturer towards temperature, pressure, and flow rates, and any other issue including straight length requirements. Locations should be selected accordingly;
3. **PVT data:** Pressure, volume, and temperature data as required for optimal measurements [1] at MPFM are available;
4. **Accessibility:** Facilities to ease the installation and removal of the meter. It is recommended to have additional space so that in future if necessary a larger system can be accommodated. Also, proper accessibility must be kept to facilitate meter data-checking operations, accommodation of test separator and headers, and any other test equipment as required. Due consideration must be given to maintenance accessibilities;
5. **Exploration:** Bypass to prevent well shutdown during testing and servicing [1]. Electrical connections: Proper power and communication, network cabling, and connections for satisfactory operation must be checked in line with manufacturer's recommendations;
6. **Sampling:** Facilities to collect multiphase fluid samples;
7. **Fixing:** Individual meter fixing and installations with requirements for straight length flow conditioners, etc.;
8. Back up and spares arrangements, as per the site conditions.

5.1.2 INSTALLATION REQUIREMENTS

General mechanical installation requirements, such as piping alignments, dimensional matching, and fitting the instruments in the pipe should be met with, to assure required straight lengths and flow conditioners are done as per manufacturer's recommendations. Also, checking of proper power supply, connections, earthing, and communication connections have been carried out as per the recommendations. All protections for the meter and/or for hazardous locations are well taken care off.

5.2.0 Brief Multiphase Commissioning Discussions

After the installation is over it is necessary to check thoroughly that the installation work has been done completely. After that the precommissioning checks, loop continuity checking, etc. are carried out. Usually the vendor requires some information on process, mechanical and operational data from the client for proper set up of the MPFM [1]. These are done in suitable drawings and documentation and a punch list is prepared. So, prior to starting commissioning it is ensured that all necessary steps have been completed. With due authorization, commissioning activities such as system testing and system checks (end to end) are carried out. System configuration tests as per relevant standard(s) are undertaken. Pressure test and communications checks are performed before the final test and performance tests are undertaken. In the final test and performance tests suitable recoding as per mutually agreed protocols are recorded and signed by the owner and the vendor to complete the procedure.

6.0.0 MULTIPHASE FLOW METERING—TESTING AND CALIBRATION

There are three main places that testing, calibration, and adjustments can be performed. These are the factory—factory acceptance test, test facility, and in situ in sequence. In cases where there is no separate test facility, the adjustments are from FAT to in situ. Various testing and adjustment facilities have been detailed in Table IX/6.0.0-1.

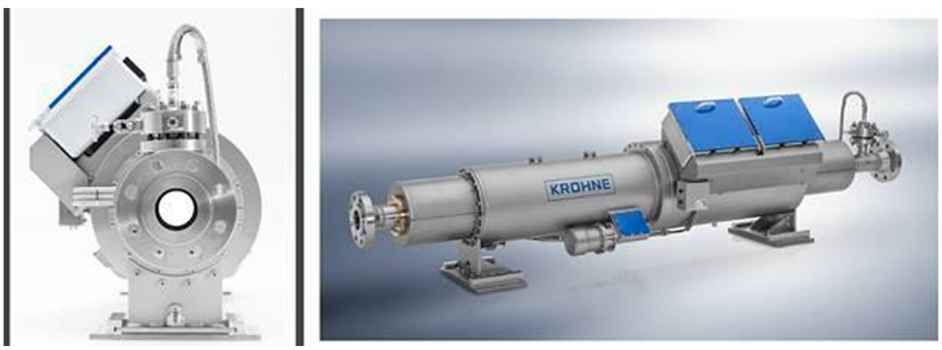
Static calibration represents the normal factory tests, whereas loop testing is dynamic testing. When the results from a calibration are assessed, one should bear in mind the significant difference between MPFMs and single-phase meters [1]. Some of the adjustments based on dynamic calibrations mainly include curve fit/matrix calibration and factory calibration.

With this the discussions on multiphase flow metering are concluded.

TABLE IX/6.0.0-1 Testing and Calibration

	Action	
Stages and Location	**Test**	**Calibration**
Factory	Functional of system	Static and dynamic
	Routine tests of instrument	Model fluid
		Purpose-built loop
Test facility	Instrument and communication check	Static and dynamic
		Nonbias
		Extended test matrix
		Reference instruments traceable to standard
		Represented fluid
		Live process fluid
In situ	Same as above with commissioning	Static and dynamic
		Baseline recording
		Phase transition issue
		Performance test
		Satellite field start up

Based on *Table 10.1 of* Instrument Engineers' Handbook, vol. 1, Process Measurement and Analysis, CRC Press (Chapter 2 flow measurement).



External and internal view of M Phase 5000. *Courtesy: Krohne Messtechnik GmbH (Magnetic Resonant Type MPFM from Krohne).*

LIST OF ABBREVIATIONS

ABS Absolute
AC Alternating current
ADC Analog-to-digital converter
AI Analog input
AO Analog output
AR Actual reading (in connection with accuracy)
CCW(/CW) Counterclockwise (/clockwise)
CMRR Common mode rejection ratio
CMV Common mode voltage
CS Carbon steel
DAS Data acquisition system
DC Direct current
DCS Digital control system
DDS Direct digital synthesizer
DEGRA Dual-energy gamma ray attenuation
DI Ductile iron/digital input
DO Digital output
DP Differential pressure
DPT Differential pressure transmitter/transducer
DSP Digital signal processing
EIT Electrical impedance tomography/type
EMC Electromagnetic compatibility
FAT Factory acceptance test
FC Fail to close (for valve)
FO Fail to open (for valve)
FSD Full-scale division (in connection with accuracy)
GOR Gas−oil ratio
GVF Gas volume fraction
HVAC Heating, ventilation, and air conditioning
IC Integrated chip/internal combustion (engine)
ID Internal diameter
I/O Input/output
IS Intrinsic safety
LCD Liquid crystal display
LDA Laser Doppler anemometry
LDV Laser Doppler velocimetry
LED Light-emitting diode
LHS Left-hand side
MFM Multiphase flow meter (see MPFM also)
MP Multiphase
MPFM Multiphase flow meter
MS Mild steel (main steam)
MUX Multiplexer
MVT Multivariable transmitter
NAA Neutron activation analysis
NB Nominal bore
NIR Near infrared
NIST National Institute of Standards and Technology
OD Outer diameter
PIV Particle image velocimetry
PLC Programmable logic controller
PNA Pulsed neutron activation
PTFE Polytetrafluoroethylene
PTV Particle tracking velocimetry
PU Processing unit
PVC Polyvinyl chloride
PVT Pressure, volume, temperature
RF Raised face/radiofrequency
RHS Right-hand side
RPM Revolutions per minute
RTD Resistance temperature detector
SIL Safety integrity level
SS Stainless steel
STP Standard temperature and pressure (Fig. I/1.1.2-3)
TC Thermocouple
TP Two phase
US Ultrasonic/United States
VDU Visual display unit
VFD Variable-frequency drive
VM Valve manifold
VMS Virtual metering system
W/O Without/water in oil (emulsion)
WRT With respect to

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CHAPTER X

SPECIAL FLOW METERS, FLOW GAGES, AND SWITCHES

Chapter Outline

1.0.0 INTRODUCTION

Starting from various principles of measurements, various kinds of flow meters have been discussed at length in previous chapters. The flow meters discussed so far are commonly found in various plants and industrial applications. Therefore, these can be considered as common flow meters. However, apart from various common flow meters there are a few flow meters which make use of some special physical phenomena for flow measurements. These are special flow meters. These are not very commonly used. However, under certain conditions and measurement constraints they are found to be extremely useful. Cryogenic condition is a special condition, and measurement of flow in that condition is not easy. Cryogenic flow meters are examples of some of the special flow meters. In some plants it is not always necessary to use flow meters for flow monitoring. Hall effect flow sensing is not a flow meter in the true sense. It represents a way to sense flow. Like magnetic pick, up this is another special way of flow sensing. Hall effect sensors are related to flow measurement in different ways. It can be used as a sensing element to compute flow in a turbine flow meter or paddle wheel flow (switch). If we look at solid flow measurement, a Hall effect sensor is utilized here also for sensing of conveyor speed measurement, which is directly related to solid flow measurement. Hall effect can be used to sense zero flow and this is also related to protection of solid flow

Plant Flow Measurement and Control Handbook. https://doi.org/10.1016/B978-0-12-812437-6.00010-X

measurement through a conveyor. Simple flow/no-flow conditions would suffice, e.g., a big fan/pump lubrication system, here there is a need to ensure that there is flow in lubrication line when the lube pump (in fact for that matter the main fan or pump) is started locally. Therefore, a simple flow/no-flow gage is sufficient. In this case, metering of flow by a flow meter would neither be cost-effective nor in many cases, on account of the short space installation of the flow meter, may it be feasible. When a big fan and/or pump is started through an auto-program or in running condition it is necessary to interlock the fan/pump with lube oil system for the safety of the fan/pump. When the lube oil flow is less, first there may be a pretrip alarm followed by tripping of the concerned fan/pump. In all such cases switches (not the flow meter) are deployed. Some use a flow switch, some use a pressure switch. In many mixing and batch controls, the flow switch is necessary for the recipe to maintain quality of the output product. In all such cases flow switches are used. In this section these special flow instruments and flow gage flow switches have been covered to complete the discussions on flow monitoring. In many cases the operating principles of these flow gages and switches are similar to flow meters but the designs and/or installations are different, so these need separate treatment.

It has been seen that Hall effect sensors are used for flow sensing in many instruments already discussed, such as turbine flow, to measure the speed of the rotating device. In the same way it can be used to detect the speed of a conveyor and/or zero speed switch for a conveyor which is used in solid flow measurement. Other than Hall effect sensors, often magnetic pickups and proximity pickups are also used. These are very useful in flow measurement. It is better to look into the details of Hall effect sensing along with other inductive pickups.

The discussion starts with Hall effect sensing.

2.0.0 HALL EFFECT SENSING AND FLOW MEASUREMENT

The Hall effect is a very effective sensing technology. It is named after its inventor, Edwin Herbert Hall, who invented it in 1879. When a metal plate is connected across a power source then charges from the battery outlet go to the metal piece and pass through it in a straight path and return to the battery to complete the current path. When the same arrangement is placed in a magnetic field perpendicular to the direction of current flow it can be noticed that, on account of Lorenz force, charge careers are deflected and move towards the edges. This is the fundamental principle on which the Hall effect has been developed. The Hall element is a solid-state device developed from a thin sheet of semiconductor material. When it is supplied with a voltage source and is subjected to a magnetic field, it responds with an output voltage proportional to the magnetic field strength, with output connections perpendicular to both the direction of current flow and direction of magnetic field. The output voltage developed is very small (μV) and requires additional electronics to achieve useful voltage levels. Therefore, the Hall element combined with the associated electronics forms the popular Hall effect sensor. This magnetic field sensor has a very wide range of applications. It can be used as a sensor for speed, flow, current, temperature, pressure, position, etc. In this connection Section 9.0.0 of Chapter IV (where short discussions on this have been provided)may be referenced also. There are a few issues pertinent to the Hall effect sensor worth noting:

1. **General sensor selection:** For selection of the sensor there are certain fundamental principles to be followed. One important issue is to identify the input and output requirements, application requirements, and match these with the major sensing device components. Engineering judgment is the only tool, such engineering judgments come only after the strengths and weaknesses of each approach are weighed. The major issues are listed here:
   - Overall cost;
   - Device availability;
   - System and device complexity;
   - Tolerance of field conditions;
   - Compatibility with other system components [1];
   - Reliability;

- System performance including repeatability;
- Maintenance issues.

2. **Hall effect as the preferred sensor:** While selecting a sensing element, cost, performance availability, and mounting facilities are normally considered as primary issues. From all these considerations, Hall effect sensors are preferred mainly on account of the following reasons:
   - *True solid state:* Fast acting, low power;
   - Static, no moving parts;
   - Long life;
   - Good performance, including high repeatability;
   - Operates with stationary input (zero speed) [1];
   - Available in analog and digital form;
   - Logic compatible input and output;
   - Wide temperature range for operation.
3. **Design requirements of the Hall effect sensor with a system:** As the Hall effect sensor is a magnetic sensing it requires a magnetic system capable of responding to the physical parameter to be sensed. Since silicon has a piezoresistive effect, the design should take care to minimize this effect. The physical parameter actually interfaces with the sensor. In most cases these are mechanical interfaces. The Hall effect sensor senses the changes in magnetic field to produce an electrical output. Here it is the responsibility of the output interface to match the output signal with the system requirements to fulfill the application objective. Therefore there are basically four blocks here, i.e., input interface (measuring parameter) with input interface, magnetic system, Hall element, and finally the output interface. This has been clearly depicted in Fig. X/2.0.0-1.

   Also, there should be a suitable interconnection amongst them according to the application requirements. It is worth noting that it is not mandatory that all four elements discussed above are necessary, e.g., for any measurement related to the magnetic field sensing system, does not require a magnetic system.

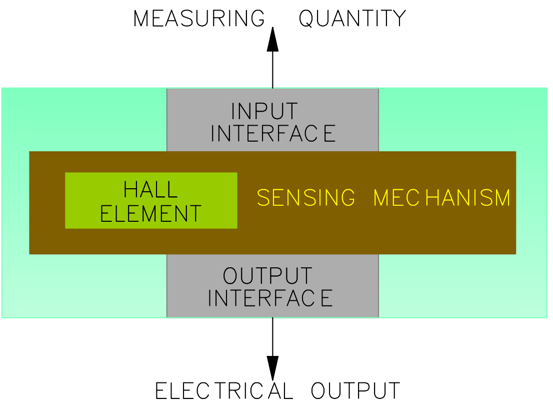

FIGURE X/2.0.0-1 General Hall effect device.

While defining the input to the sensor it is necessary to take care of the following:

- Input parameter range values with possible rate of change (maximum and minimum);
- Factors which can affect the measurement (temperature/EMI);
- Safety factor to be chosen;
- Probable sources of error;
- Allowed tolerance limits;
- Ambient conditions.

Similarly, output characteristics are also guided by the following manner:

- Electrical characteristics, i.e., output forms in current, voltage, pulse train, logic levels, etc.;
- For digital output meaning and level of signals for 0 and 1;
- Output at sensor OFF condition and interpretation;
- Output load value and types (e.g., resistive);
- Interconnection details with allowed cable length;
- Output characteristics, i.e., sourcing/sinking;
- Performance requirements;
- Available space and weight.

There is also requirement of system definition which includes but is not limited to the following:

- Gap (minimum/maximum) between Hall element and magnet;
- Maximum minimum allowed magnet travel;

- Mechanical linkage if required;
- Sensor output type (to match source/sinking type);
- Allowed operating and storage temperature;
- Selection of the magnetic mode, magnet, Hall effect sensor, and functional interface [1];
- Matching of input/output requirements.

We now examine the theory of operation for Hall effect sensing.

2.1.0 Theoretical Background of Hall Effect

In this section the theory of operation of Hall effect sensing is discussed. The Hall element is a thin sheet of semiconducting material which can pass current through it. So when a voltage is applied to terminals 1 and 2 in Fig. X/2.1.0-1, the current will flow undisturbed from terminal 1 to 2 and if voltage is measured across terminals A and B there will be zero potential difference, when there is no magnetic field applied. When a magnet is brought near the Hall element, a Lorentz force is exerted on the current. This force disturbs the current distribution, based on the magnetic pole present near it, the charges are deflected from each other rather being shifted towards the sides of the Hall elements, as shown in Fig. X/2.1.0-1. As a result there will be positive and negative charges at the two ends. Therefore, when voltage is measured across the Hall element there will be a potential difference between terminals A and B. This is Hall voltage, V_H. It is worth noting that the voltage developed will be proportional to the vector cross-product of strength of current (in ampere) passing through the semiconductor and magnetic flux density (in Tesla) applied as shown in Eq. X/2.1.0-1.

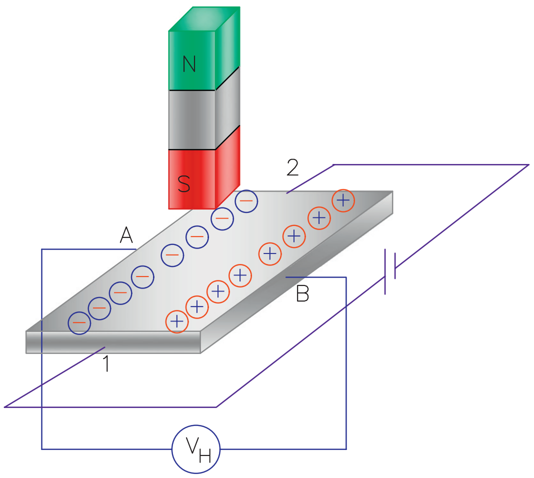

FIGURE X/2.1.0-1 Hall effect sensing principles.

$$V_H = R_H \cdot \frac{I}{T} \times B \qquad \text{(X/2.1.0-1)}$$

This also indicates that the output is perpendicular to both the direction of current and the magnetic field. R_H is the Hall effect coefficient and T is the thickness in mm. The strength of voltage developed is in the order of a few microvolts, typically R_H is 7 μV/Vs/Gauss. Naturally, in order to make the voltage workable for all practical applications it is necessary that there will be some signal conditioning units associated with the Hall element. Common mode voltage is an important issue here. If no magnetic field is applied, but there is some voltage at a terminal with respect to the ground, then it is common mode voltage and is the same at each output terminal. In order to get rid of this, like any other analog circuit, the first stage of the amplifier is a differential amplifier. A typical Hall element with signal conditioning unit(s) is discussed in the following section.

2.2.0 Hall Effect Sensor Types

Hall Effect sensors are of two types: analog and digital. In this section both types are discussed, starting with the analog type.

2.2.1 ANALOG TYPE SENSOR

The analog sensor is depicted in the first part of Fig. X/2.2.0-1 i.e., up to the first output. As shown in the figure, a regulated voltage source drives the current through the Hall element, which is subject to a magnetic field. As the voltage is regulated it is constant, thus in analog sensors the output voltage is proportional to the strength of the magnetic field to which it is

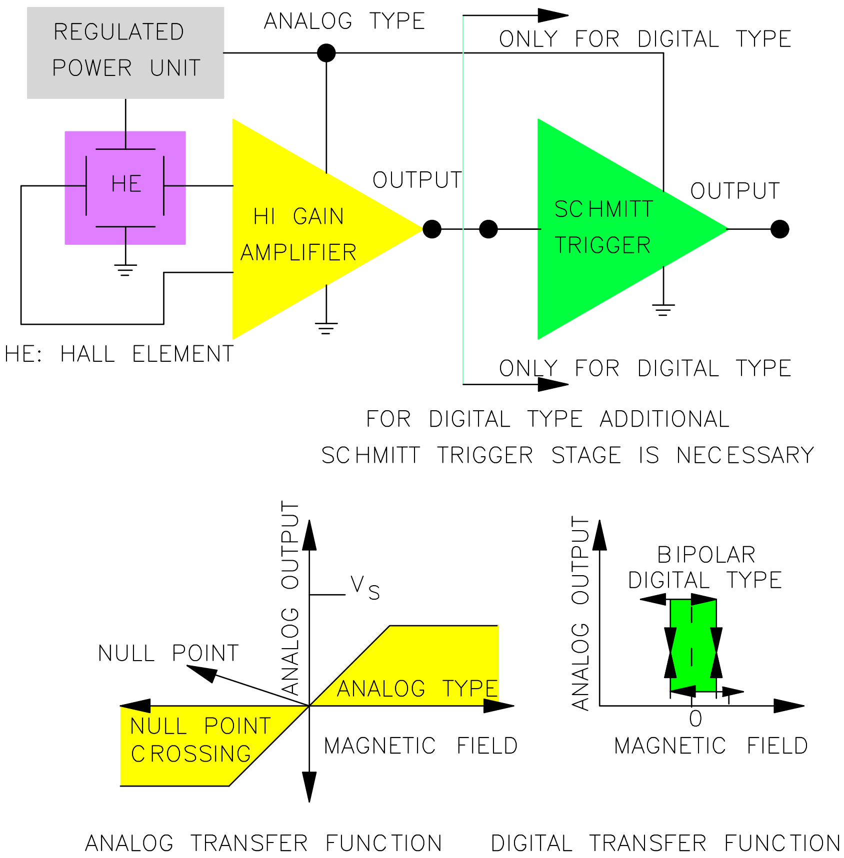

FIGURE X/2.2.0-1 Hall effect sensing types.

exposed. Depending on magnetic polarity there will be different ways that the charges are migrated towards the periphery of the Hall element. As a result of this the output of the amplifier will be either positive or negative. This would then necessitate both plus and minus power supplies. In order to avoid this, a fixed bias is introduced into the differential amplifier. Therefore, when a positive magnetic field is sensed, the output increases above the null voltage and when a negative magnetic field is sensed, the output decreases below the null voltage, but remains positive. Therefore, output is always positive. Naturally, when there is no magnetic field applied, the bias value would appear on the output. This is referred to as null voltage, which is the crossing point of the voltage output curve with the magnetic field axis, i.e., where the positive side increasing output curve meets with the negative side increasing curve in Fig. X/2.2.0-1. As is seen in this figure, as the magnetic strength is increased in either side the output voltage changes proportionately across the null point—but how long can it go? Theoretically it can go up to the supply voltage level, but before that it is saturated as shown. Transfer function represents a graph or equation of output in terms of input. An analog type sensor transfer function is characterized by sensitivity, null offset, and span as shown. Sensitivity is defined as the change in output resulting from a given change in input, i.e., the slope. Span and null points are also very well shown in Fig. X/2.2.0-1 and can be easily arrived at.

2.2.2 DIGITAL TYPE SENSOR

As the name implies, digital type sensors give digital output. It is the same as an analog type with an additional stage as shown in Fig. X/2.2.0-1, i.e., the second output after the Schmitt trigger stage. A basic analog circuit has been modified with the use of a Schmitt trigger. A Schmitt trigger

works basically as a comparator. It compares the output of the differential amplifier with a set point/ reference. As long as the output is greater than the set point the output is logical 1 and below that it is logical 0. Therefore, the sensor has an output that is just one of two states: ON or OFF. Hysteresis is included in the Schmitt trigger circuit for jitter-free switching [1]. Like any other hysteresis loop, here also there are two distinct reference values at times referred to as set and reset depending on whether the sensor is turned ON or OFF. The transfer function for a digital output Hall effect sensor with hysteresis is shown in Fig. X/2.2.0-1. As the magnetic field is increased, no change in the sensor output will occur until the reference/set point is attended. Once the operate point is reached, the sensor will change state, e.g., from the OFF state to the ON state and any further increases in magnetic input beyond the operate point do not have an effect. The point where the changes occur is referred to as the set point. When the magnetic field is decreased it will remain in the ON state until a point is reached when the output changes state from the ON to OFF state. Other than an ideal system this point will be separate from the set point and is called the reset point. The differential between the set and reset points is the hysteresis and serves the useful function of eliminating false triggering. The input characteristics of a digital sensor are defined in terms of set and reset points, and differential. Depending on the set and reset points the sensitivity and resolution are determined. Since these characteristics change with temperature and from sensor to sensor, they are specified in terms of maximum and minimum values. Maximum operate point refers to the level of magnetic field that will insure the digital output sensor turns ON under any rated condition. Minimum release point refers to the level of magnetic field that insures the sensor is turned OFF [1]. Digital output may be unipolar or bipolar (as shown in Fig. X/2.2.0-1). When unipolar both poles of magnet output are positive but values are different. On the other hand, when bipolar it is around the zero point as shown.

2.3.0 Magnetic System

In Hall effect sensors, physical parameters such as position, speed, and flow are converted into electrical output in the presence of a magnetic field. Therefore, it is needless to say that magnetic field strength has a good influence on the operation of the sensor. This concept has been depicted in Fig. X/2.3.0-1A. Naturally the configuration and orientation of the magnetic field with respect to the Hall element are extremely important. There are two types of magnetic field: unipolar and bipolar.

2.3.1 UNIPOLAR MAGNETIC SYSTEM

In a unipolar magnet only one pole is towards the sensor and the other is away, as shown in Fig. X/ 2.3.0-1B. Unipolar system can be two types viz. "head on" type and "slide by" type as shown in Fig. VII/2.3.0-1B.

1. **Unipolar head-on mode:** In case of a head on, the magnet's direction of movement is directly toward and away from the sensor, with the magnetic lines of flux passing through the sensor's reference point. In Fig. X/2.3.0-1B the south pole of the magnet will approach the sensing face of the Hall effect sensor. In the unipolar head-on mode, the relation between Gauss and distance is given by the inverse square law. Distance is measured from the face of the sensor to the pole of the magnet, along the direction of motion. Magnetic filed versus distance have been shown in Fig. X/2.3.0-1B.
2. **Unipolar slide-by mode:** In this mode, the sensor and magnet have a vertical gap and a magnet is moved in a horizontal plane sidewise. Distance in this mode is measured relative to the center of the magnet's pole face and the sensor's reference point in the horizontal plane of the magnet. The magnetic field versus distance relation in this mode is a bell-shaped curve, which is also shown in Fig. X/2.3.0-1B.

2.3.2 BIPOLAR MAGNETIC SYSTEM

In a bipolar system, as the name suggests, there will be two poles of the magnet approaching and

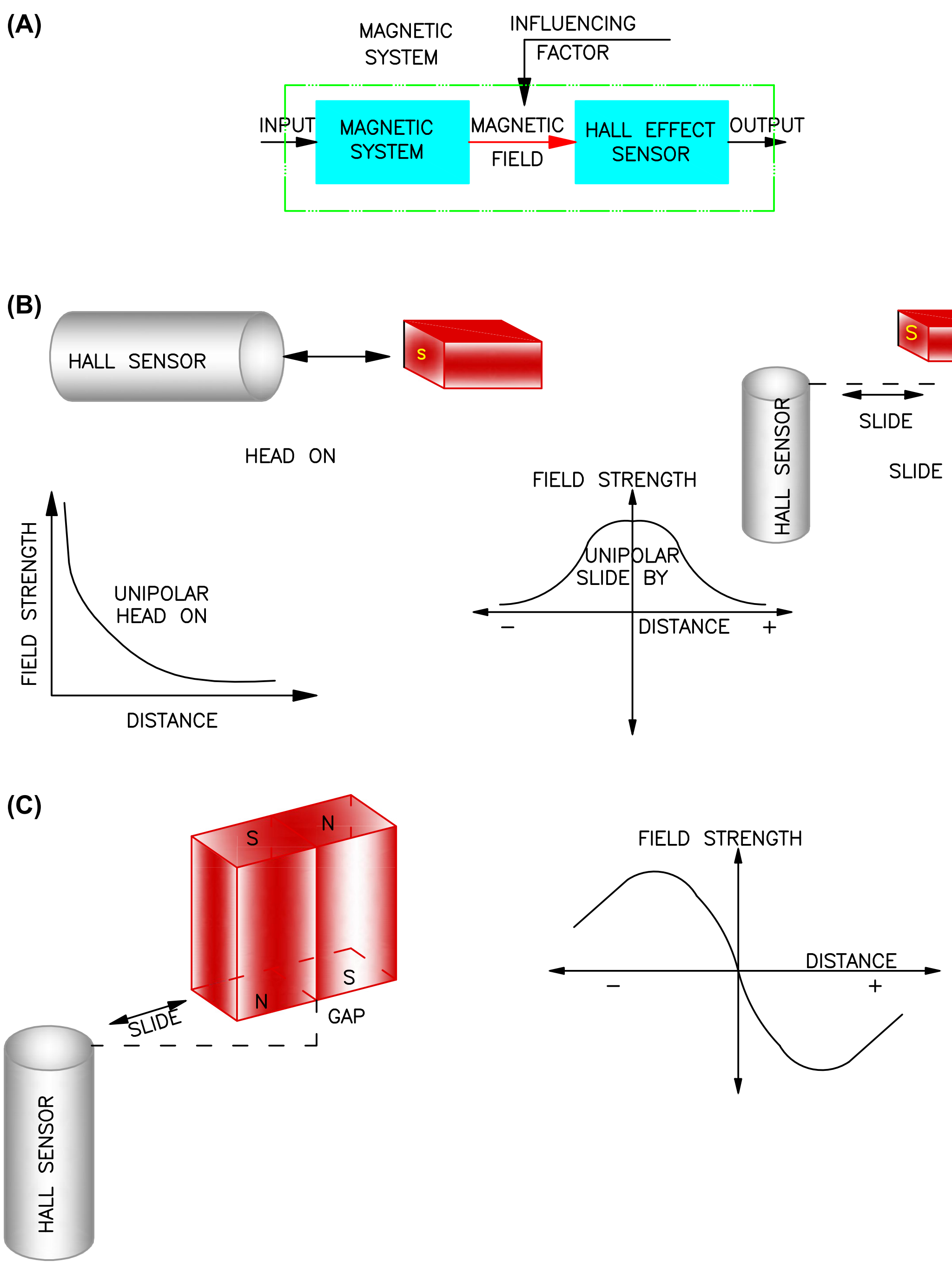

FIGURE X/2.3.0-1 Magnetic system of Hall sensor. (A) Effect of magnet on sensor. (B) Unipolar magnetic system. (C) Bipolar magnetic system. *(C) Developed based on Hall Effect Sensing and Application, Honeywell (Technical internet document). https://sensing.honeywell.com/hallbook.pdf. Courtesy: Honeywell.*

going away from the sensor. In a bipolar system a slide-by mode is possible. A bipolar system with bipolar slide-by mode has been depicted in Fig. X/2.3.0-1C. Here there are basically two sets of magnets moving in the same fashion as the unipolar slide-by mode. In this mode, distance is measured relative to the center of the magnet pair and the sensor's reference point. The Gauss versus distance relationship for this mode is an "S"-shaped curve as shown in Fig. X/2.3.0-1C [1]. There is another possibility of a magnet in ring form in this manner.

For further reading and comparison the chart in Ref. [1] may be referenced.

2.4.0 Hall Sensor Features and Applications

Hall effect sensors have a number of features and applications worth noting. However, our discussions are limited to flow applications only. As speed measurements and zero speed monitoring form a part of solid flow measurements these have been included here.

2.4.1 FEATURES OF HALL EFFECT SENSORS

In flow sensing the following features of Hall effect sensors are important:

1. Wide working voltage (3.8−30 VDC);
2. Low power consumption;
3. Maximum current drawn is <20 mADC;
4. Performance of accuracy around 1% possible in some cases but normal accuracy is lower than this;
5. Highly durable;
6. Open collector output possible;
7. Wide range of temperature −40 to 150°C;
8. High humidity-withstand capability;
9. All SS construction possible;
10. Nonintrusive measurement;
11. Suitable for hazardous applications with FM/other certification from approving authorities.

2.4.2 APPLICATIONS IN FLOW MEASUREMENT

It is worth noting that the Hall effect sensor is always used with any flow transducers as measurement of any desired parameter of the flow transducer, e.g., the impeller speed of a turbine flow meter is a measure of the flow rate. The Hall effect sensor can be used to measure the flow in an indirect way. Therefore, there are several different types of flow transducers that can be used in conjunction with the sensor to measure/compute flow rate in the conduit.

Fig. X/2.4.0-1 illustrates a typical flow measurement scheme. The fluid to be measured flows through the sensor and is directed past the paddle wheel. The paddle wheel rotates and one Hall effect sensor as shown is mounted at the sensor case near the vicinity of the paddle wheel. As each of the paddle wheel edges passes the sensor it interrupts the magnetic field created by the magnet with the sensor being interrupted, hence V_H of the sensor results small AC pulses at the sensor output. This small AC output of the sensor through the signal conditioning unit, including the Schmitt trigger, produces a digital signal output proportional to the flow. As the flow rate through the meter increases, there will be more pulses per second. As there are multiple pulses per rotation and the sensor is linear with regard to the number of pulses per volume irrespective of flow rate it is easy to interface with the

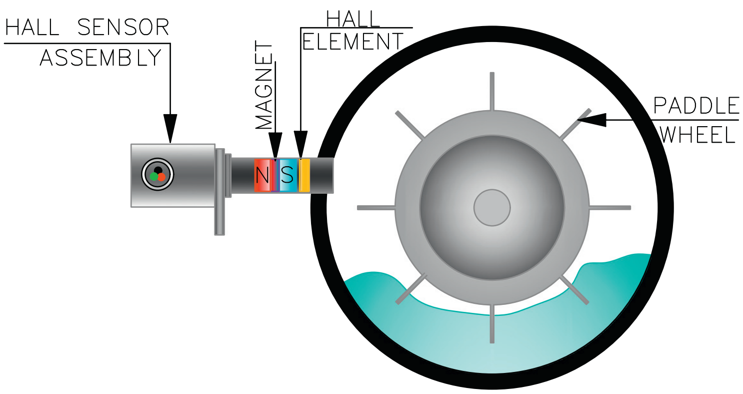

FIGURE X/2.4.0-1 Hall effect sensor in flow measurement.

microcontroller, an essential part to run the embedded system. A embedded microcontroller regulates the entire operation of the Hall effect sensor.

2.4.3 APPLICATIONS IN SPEED SENSING AND MEASUREMENT

The speed sensor is one of the most common applications for a Hall effect sensor. It is even used to measure the speed of large turbines. This is an example of magnetic measurement. The required magnetic flux to operate the sensor may be furnished by magnets mounted on the shaft or hub or by a ring magnet, typically as shown in Fig. X/2.4.0-2.

In this figure it can be seen that in one case a magnet is mounted on the shaft, whereas in the other case a magnet is embedded on the hub. In both cases, as the shaft rotates there will be a change in the magnetic flux density so that the Hall effect sensor can measure the number of rotations per minute of the shaft. Alternatively, without mounting a magnet on the shaft/hub, it is also possible to measure the speed in a similar fashion shown for flow in the paddle wheel (or turbine meter). The main issue is to bring about the change in the magnetic field due to rotation of the shaft/flow so that it can be measured by the Hall effect sensor. Most of the RPM sensor functions of interest to us are listed here:

1. Speed control;
2. Control of motor timing;
3. Zero speed detection;
4. Under or over speed detection;
5. Disk speed detection;
6. Shaft rotation counter;
7. Bottle counting (in dispensing machine);
8. Flow-rate meter;
9. Tachometer pick-ups.

2.5.0 Specification of Hall Sensors

A brief specification of a Hall effect sensor has been enumerated in Table X/2.5.0-1.

Now we look for another kind of pickup used in flow meters and for speed measurement of conveyor related to solid flow measurement, for which magnetic pickup and a proximity sensor are commonly used.

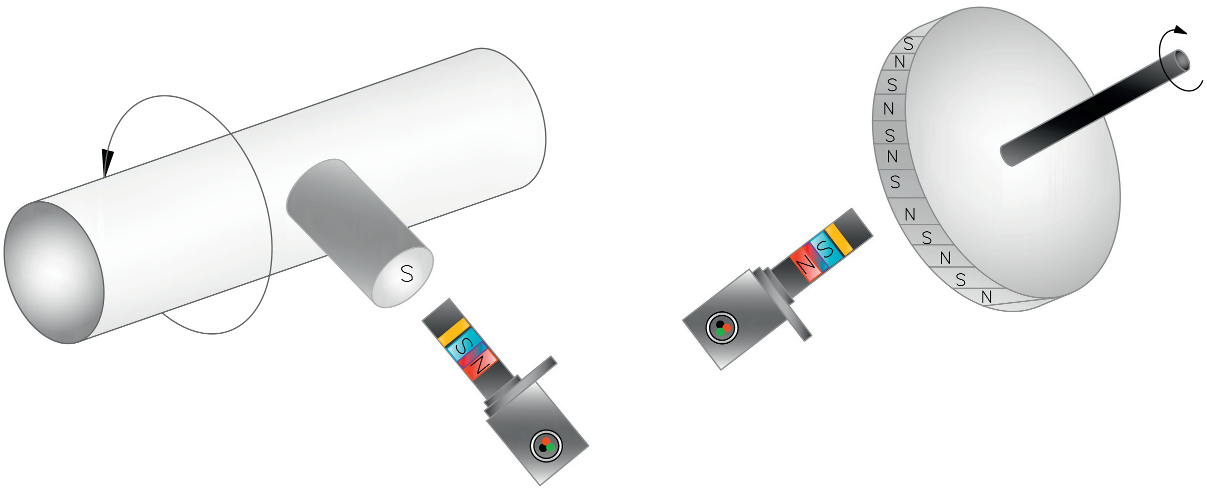

FIGURE X/2.4.0-2 Hall effect sensor for speed measurement.

TABLE X/2.5.0-1 Specification of Hall Effect Sensor

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Supply voltage	3.8–30 VDC		
2	Current	Normally <20 mADC		Sensor specific
3	Operating frequency	0–20 KHz (typical)		
4	Rise time	To specify		
5	Fall time	To specify		
6	Types	Analog/digital		
7	Output	Voltage/current (analog) or open collector source/sink (digital)		
8	Output function	Described in main body		
Materials of Construction (MOC) for				
9	Body	Stainless steel SS 316		
Connection and Mounting Details				
10	Process	Threaded		
11	Electrical	½″ NPT/ET		
Performance and Other Details				
12	Accuracy	±1 FSD		To specify
13	Certification	Necessary certification from appropriate authority for hazardous applications		
14	Application of interest	Flow/speed		
15	Operating Temperature	−40 to 150°C		
16	Special feature	To specify		

3.0.0 MAGNETIC AND PROXIMITY PICKUP AND FLOW MEASUREMENT

Like Hall effect sensors, magnetic pickups and proximity pickups are commonly used in flow meters as well as for measurement of speed for conveyors necessary for solid flow measurements. Both principles are quite close, and so are covered in this section. In this section brief discussions on each have been presented. In this connection Section 2.1.3 of Chapter V may also be referenced for short discussions on pick ups.

3.1.0 Magnetic Pickup and Flow Measurement

When one recalls the discussions on turbine/PD flow meters, magnetic pickups are extensively used. Also, for speed measurement of conveyor belts, magnetic pickups are used extensively. We now start the discussions on magnetic pickup working principles.

3.1.1 MAGNETIC PICKUP WORKING PRINCIPLES

The magnetic pickup produces a voltage output when any magnetic material moves through the magnetic field at the end of the pickup. Any device which produces a dynamic discontinuity of magnetic material in the field of the pickup will produce an electrical voltage. A magnetic pickup consists of a coil wound around a permanently magnetized probe. When any ferromagnetic objects—such as gear teeth, turbine rotor blades, slotted discs, or shafts with keyways—cross the

probe's magnetic field, the flux density is modulated. On account of flux density modulation or cutting of the lines of force by the object, an AC voltage will be induced in the coil. One complete cycle of voltage/pulses will be generated for each object passed. If the objects are evenly spaced on a rotating shaft, the total number of cycles will be a measure of the total rotation, and the frequency of the AC voltage will be directly proportional to the rotational speed of the shaft. The magnetic speed pickup (MPU) is used to detect the speed of the prime mover. Therefore, in the area of flow measurement it can be used to measure the speed of the conveyor in solid flow measurement or it can be used with fluid flow meters, such as turbine and PD meters, to measure fluid flow in the conduit. Output waveform is a function of the following:

1. Rotational speed of the moving object;
2. Gear-tooth dimensions;
3. Gear teeth spacing (gaps between gears);
4. Dimension of the pole-piece (diameter);
5. Air gap (between the pickup and the moving object).

Therefore, for optimum response the above parameters need to be adjusted, and the pole piece should be less than or equal to both the gear width and the dimension of the tooth's top. The air gap should be as low as possible, normally around 0.25 to 1 mm depending on the cases.

3.1.2 INFLUENCING FACTOR FOR MAGNETIC PICKUP

As discussed above, the performance of a magnetic pickup is influenced by a number of factors. The output voltage of a magnetic pickup is affected mainly by three factors:

1. Generated voltage is proportional to the surface speed of the monitored magnetic material.
2. With a decrease in the air gap between the magnetic pickup and the surface of the rotating object, voltage increases.
3. Voltage waveform is determined by the size and shape of the gear tooth in relation to the size and shape of the pole piece.

For any given speed and clearance conditions, there will be a maximum power output when the path is filled with a relatively infinite mass of ferromagnetic material. Therefore, it is filled with an infinite mass of ferromagnetic material at one instant and a complete absence of ferromagnetic material (i.e., air) the next. As a result of this there will be quick changes in the lines of force, which results in the generation of AC voltage. The following are reasonably good conditions:

- When the cross-section of the exciting masses is equal to or greater than that of the pole piece;
- When the gap is equal to or greater than three times the diameter of the pole piece.

3.1.3 INSTALLATION OF MAGNETIC PICKUP

Magnetic pickup is mounted radially to the outside diameter of the desired gear made up of ferromagnetic either through the housing or on a rigid bracket. The mounting can be in the vertical or horizontal plane as shown in Fig. X/3.0.0-1.

In order to get rid of EMI and other pickups, a shield of nonmagnetic material may be installed between the gear and the pickup if necessary for physical shielding. Additionally, there may be a threat that electromagnetic force may be generated by eddy currents in the shielding material. Therefore, suitable protection should be taken care of to stop this from happening.

There is another kind of pickup called proximity pick up, which is mostly used for zero speed detection, as discussed in the next section.

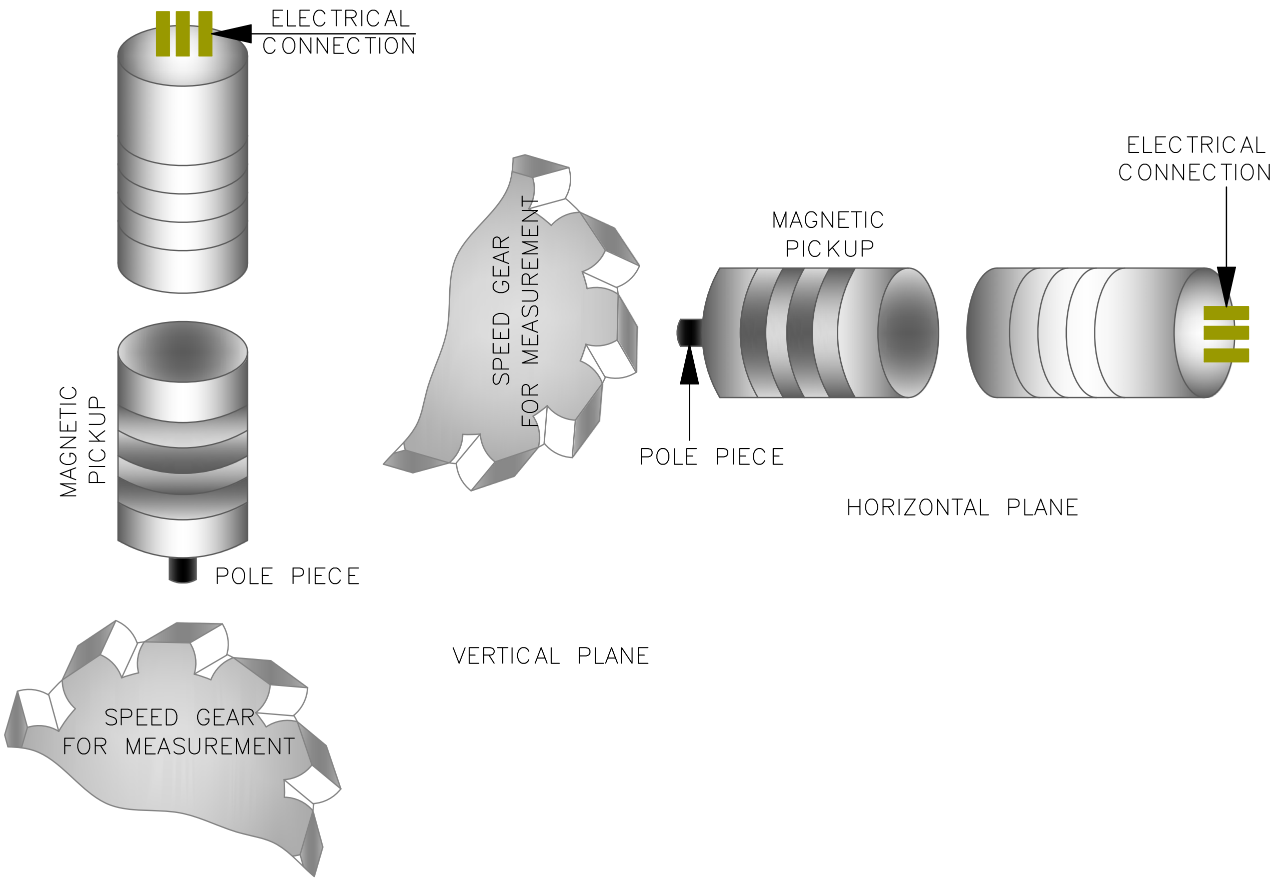

FIGURE X/3.0.0-1 Magnetic pickup.

3.2.0 Proximity Pickup

Proximity sensors have versatile applications, and are used for vibration and speed measurement. In our case it is mainly used for zero speed sensing for large pieces of equipment because of its abilities to operate with a large air gap and at low surface speeds. Zero speed sensing by proximity switch is important for solid flow measurement by (say) Belt feeder or weigh feeder etc. The output of these pickups depends solely on the position of ferrous discontinuity such as gear teeth. Short details of the operating principle are given here.

3.2.1 OPERATING PRINCIPLE OF PROXIMITY PICKUP

Proximity sensing is inductive sensing. It consists mainly of four blocks. These blocks are the oscillator, magnetic/inductive coil, detector, and output stage, which could be a Schmitt trigger. With a DC power supply, the oscillator produces an oscillating AC signal to generate a fluctuating magnetic field around the coil at the sensing surface. This magnetic field is like a donut and leaves the face surface. When any metal object moves into the inductive proximity sensor's field of detection, on account of the cutting of the magnetic lines of force by the metal object, an Eddy current/circuit is built on the metallic object and this will try to oppose the oscillator circuits' oscillating magnetic field. The detector circuit continuously monitors the magnetic field strength to produce output. The Schmitt trigger is used for production of output or stops output, depending on the NPN/PNP transistor configuration of the output stage. Thus when the magnetic field strength goes below the set point, a switching action in the form of output as described above will take place.

3.2.2 INSTALLATION PROXIMITY PICKUP

The proximity pickup is mounted outside the diameter of the desired gear made up of ferromagnetic material either through the housing or on a rigid bracket. As shown in Fig. X/3.0.0-2, the proximity pickup can be mounted for radial as well as axial measurements.

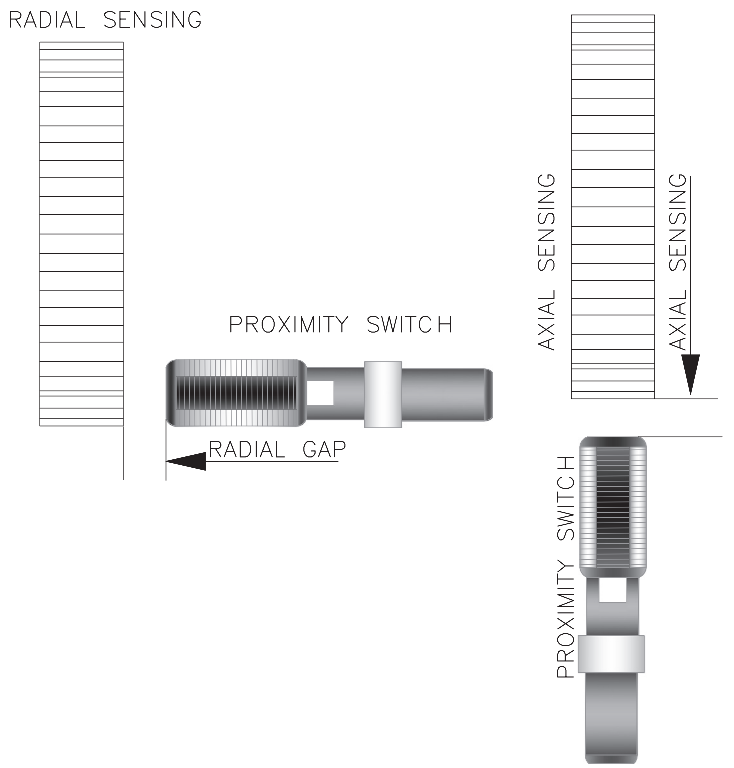

FIGURE X/3.0.0-2 Proximity pickup.

3.3.0 Signal Conditioning Unit

Normally these pickups need a loop-powered flow monitor that converts a meter's pick signal to a 4–20 mA current output. The linear output is proportional to the meter's flow rate. These signal conditioning units should be small enough to fit inside any meter box. Also setting should be easy and they should be compatible meters. Often this is referred to as the preamplifier stage, when there is separate signal conditioning electronics. This connects the meter's register with the pickup through a cable. Otherwise these can generate 4–20 mADC in two wires to connect to an external device, e.g., a PLC. Since these are loop powered, these are connected to the external 24 VDC with a wire and through another wire they provide the 4–20 mA signal output. Generally they are made up of ABS/polycarbonate blend [2].

With this the discussions on various pickups come to an end and we now investigate another special type of flow measurement—cryogenic flow measurement.

4.0.0 CRYOGENIC FLOW MEASUREMENT

There have been drastic changes in cryogenics industry in the past few years. There has been greater demand for cryogenic and liquefied gases, which means that there has been an increased demand for effective measurement. At cryogenic conditions, liquids offer little lubrication for moving parts and the thermal shock of fluids at

Cryogenic liquid and cryogenic treatment: *Any liquid which boils under normal condition at a temperature below −90°C is referred to as cryogenic liquid. Most of the gases such N_2, H_2, O_2 inert gases (e.g. Ar, He), liquefied natural gas (LNG) and ethane etc. have their boiling points below that. So, in liquid condition, these fall under this category. All these gases are transported and stored in liquid conditions for facilitating their handling. From this point of view study of cryogenic liquid and their flow measurements are important. Cryogenic materials have special property and cryogenic treatment refers to processing cryogenic liquids.*

FIGURE X/4.0.0-1 Cryogenic liquids and their treatment.

these low temperatures is very problematic for transportation. Keeping elements cold, below boiling points—and also ensuring that these materials are in their purest forms—is challenging [3].

On account of the temperature and two-phase nature, cryogenic fluids show different behavior and special treatment is called for. For idea on Cryogenic liquids and their treatments Fig. X/4.0.0-1 may be referenced. As such, two-phase flow behavior is not easily predictable, and in case of cryogenic liquid the operating temperature is too low. So handling of cryogenic liquid is more tough than normal two phase fluids. Cryogenic fluids find their applications in a wide variety of applications, including propellants for aerospace applications, storage of industrial and life support gases, and coolants for superconducting magnets. Natural gas (NG) is also important for the energy system and power generation. Natural gas is handled cost-effectively in liquefied form. Therefore, flow measurement of liquefied natural gas (LNG) is a common example for cryogenic flow measurement for storage and handling. In aeronautics and aerospace, cryogens are commonly seen as fuels for propulsions systems. In space-shuttles liquid hydrogen (LH) and liquid oxygen (LO) are used, with liquid nitrogen being used (LN) in coal mines. The German V2 rocket developed in World War II was the first aerospace application developed on a large scale that used cryogenic fluids as propellants [4]. Since then, numerous propulsion systems using cryogens have been developed. As indicated above, because of the two-phase nature of cryogens and the presence of bubbles within the liquid interference, it is very difficult to have precise measurement. Orifice, Venturi in DP method, turbine flow meters, Coriolis flow meters, vortex flow meters, and US meters have been applied for cryogenic applications but there are many limitations to their use. From the literature, deployment of microwave flow meters with suitable DAS has also been noted.

4.1.0 Discussion on Cryogenic Flow Measurements

Various constraints associated with cryogenic instrument types and brief selection criteria are discussed in this section.

4.1.1 CONSTRAINTS OF VARIOUS CRYOGENIC FLOW METER TYPES

As indicated above, several types of conventional instruments have been applied for cryogenic applications, but each has some limitations. A few of these limitations have been discussed in this section. These constrains include but are not limited to the following:

1. **Orifice plate DP meter:** Unnecessary resistance is offered to liquid flow and this creates additional permanent pressure drop than under normal situations. Extra permanent pressure drop limits its use in many cryogenic applications under saturated conditions.
2. **Venturi DP meter:** In the case of a Venturi, due to extra pressure drop there can be cavitations.
3. **Turbine flow meter:** During cooling there is the possibility of higher oscillation, which damages the meter. Also at cryogenic conditions, when the flow alternates between bubbles and liquid there can be serious damage to the bearing.
4. **Vortex flow meter:** Vortex flow meter performance is acceptable only at lower Reynolds number, otherwise the accuracy deteriorates. For that reason, a noninvasive ultrasonic flow meter is also a good choice.

However, in the majority of cases, especially for thermal performance assessment and

calculations, mass flow rate is required to be assessed and to be used for mass and heat balancing. Naturally, in all the above cases of metering, density measurement is required in conjunction with the flow measurement to get the mass flow rate. Therefore, to obtain better performance and accuracies expensive and complicated calibrations at *working* temperatures need to be performed [5]. Mass flow measurement in that case is a preferred one as in such cases density measurement is not required.

5. **Coriolis flow meter:** With a Coriolis meter, measurement is carried out with the help of vibration of the tube, whose modulus of elasticity changes with temperature. Liquid Nitrogen, Carbon dioxide, Argon, LNG and LPG are some of the examples where Coriolis mass flow meters are used extensively. Therefore suitable temperature compensation cannot be avoided. However, in most cases these can be a constant factor and so expensive calibration arrangements can be avoided but temperature measurement and compensation will be necessary.
6. **Summary of major constraints:** From the discussions above one can infer that there are major issues/criticality associated with cryogenics, which are summarized here:
   - Measurement difficulties and inaccuracies come from the two-phase nature of cryogenic liquid;
   - Selection of materials for operating temperature;
   - Proper and actual calibration at operating temperature;
   - Density correction for volumetric flow measurement and temperature correction factor modulus of elasticity in the case of a Coriolis mass flow meter.

   We now investigate various instruments normally used for cryogenic liquids, including LNG.

4.1.2 SELECTION OF FLOW METER IN CRYOGENIC APPLICATIONS

Choice of a correct and accurate meter is extremely important for making an investment. Also, taking the decision calls for a good knowledge of the industry. This is especially important when transporting cryogenic materials [3]. For meter selection, the following points need to be considered.

1. **Quality:** The designs and calibration of the meters must meet the highest standards of quality, with independent verification of the same. In the case of cryogenic applications, meters must be precision-crafted from the best available materials by skilled machinists so that they are able to withstand harsh conditions, including the capability to handle a wide range of temperature, [3] with a lower temperature limit $<-200°C$.
2. **Reliability:** Material quality, workmanship, proper installation, and calibration of the meter in operating conditions are key issues for reliable operation of the meter. Any meter with no moving parts always has an edge over these with moving parts in cryogenic applications. Therefore, meters with moving parts should have quick fault detection and replacement of parts.
3. **Precision:** Turbine meters should be equipped with a specially designed turbine rotor that spins freely. As the rotor spins, it affects the magnetic field provided by the magnetic pick-up, which is interpreted by the flow monitor and expressed as a flow-rate readout. In addition to the need for a high-quality meter, it is also important to have a monitor that displays in real time.
4. **Accuracy:** Meter accuracy is also important for meter selection. Independent calibration provides a greater level of accuracy and reliable operation.

In the following sections short discussions on various types of instruments used in cryogenic applications are given. It is worth noting that all these meters are conventional meters already discussed in previous chapters and so are not repeated again here. In the following sections, only special relevant parts required for cryogenic applications have been discussed. For details about any of these meters the relevant sections and chapters in this book may be referenced.

4.2.0 Differential Pressure Type Cryogenic Flow Measurement

The DP method is one of the oldest methods applied for cryogenic application. We now discuss its working method with its pros and cons.

4.2.1 DP TYPE FLOW MEASUREMENT METHODS

When differential pressure/head type flow meters discussed in Chapter II are recalled it can be seen that the measuring principle of these types of flow meters uses Bernoulli's equation to measure the flow of fluid in a conduit. On account of a restriction introduced in the conduit, as per Bernoulli's equation, there will be a pressure drop across the restriction. From Bernoulli's energy balance equation, this pressure drop across the restriction is proportional to the square of the flow rate. In the case of an orifice plate this differential pressure is measured between the upstream and downstream of the orifice plate. In the case of a Venturi, DP is measured between the upstream and throat section. The nonlinear relationship between flow and DP, as stated above, can have a detrimental effect on the accuracy and turndown of DP meters. The major advantage of DP type flow meters comes from low cost, with multiple versions possible for different fluids and measurement objectives and it being approved for custody transfer applications. Also, the measurement scheme is easily understood and well established. Added to the above, these can be easily coupled with temperature/pressure sensors to provide mass flow for steam. However, the measurement scheme is not direct, instead flow is inferred from DP. Also, rangeability and accuracies are not good because of the nonlinear relationship, and accuracy is dependent on both the flow element (mainly) and DP measuring instrument (highly accurate smart transmitters are available). These meter types can and have been applied for cryogenic applications also.

4.2.2 DP TYPE FLOW METERING AND CRYOGENIC APPLICATIONS

Cryogenic plants in earlier days used to have DP type meters installed at room temperature connected through long impulse lines. In such cases the accuracies suffer due to the following reasons:

- Lack of proper calibrating equipment operating at cryogenic temperature, the calibrations are done at room temperature and then calculated/estimated by extrapolating for cryogenic conditions from reading at room temperature.
- As stated during the initial discussions, there can be a two-phase issue, as a result liquid vapor interfaces inside the impulse lines and they may be changing states, giving rise to fluctuation in reading, especially because liquid vapor interfaces in two tubes will not be the same.

Modern transmitters are available to withstand cryogenic temperature and most of these are tested at NIST using liquid nitrogen (LN2) as a flowing media, with a boiling point of 77K (−321°F/−196°C). This is especially so when an integral orifice is used, e.g., 3051SFC Compact Conditioning Flow meter of Emerson (Rosemount). Large temperature gradients present concerns when O-rings, glands, welds, or dissimilar metals are present in the flow stream. Therefore, suitable care should be applied. At cryogenic conditions, liquids lose lubrication property for moving parts and this is another challenge for instruments with moving parts, such as turbine and positive displacement flow meters. It is important that the measurement does not have any moving parts, and hence it should be inherently reliable and often can be used in space applications (without manning). Venturi in liquefied helium (LHe) is common. However, on account of the sharp restriction, a Venturi is always preferred because of the larger pressure drop which can locally trigger flashing of liquid

and/or give rise to cavitations to reduce accuracy and bring in instability into the measurement. As a corollary to this it could be argued that the inner surface of the flow element must be highly polished.

Standard wrought austenitic stainless steels are used extensively for cryogenic applications, even for temperatures as low as the boiling point of liquid helium (−269°C). Depending on the availability in the particular form or size required, the most widely used wrought stainless steels for cryogenic service are AISI types 304 and 304L, while types 316, 316L, 321, and 347 are also used. These materials are used for flow elements and impulse lines, as well as transmitter wetted parts. This is applicable for other instrument types also.

When instruments are tested individually, an accuracy of ≤±1.5% is achievable [6]. This will also ensure better repeatability. Testing of the meter and straight length in operating conditions is extremely important.

4.3.0 Turbine Meter in Cryogenic

As already discussed in Section 2.4.0 of Chapter V, in turbine flow meters, on account of fluid flow, the rotor of the turbine rotates in a suitable bearing. The rotational speed of the turbine is measured by magnetic (Hall effect) pickups. The turbine meter has moving parts and, as stated earlier, liquids offer little lubrication for moving parts in cryogenic conditions. Therefore, it is vulnerable when subjected to cryogenic conditions unless highly precise design, sizing, workmanship for manufacturing with most suitable materials, proper installation, and calibration of the meter are undertaken. Also, as the turbine meter bearing and other parts may get damaged, the importance of quick fault prediction and detection by associated electronics and ways and means for quick replacement of parts should not be overestimated. There should be well-protected insurance against low performance; suppliers who calibrate both in-house and independently offer a more conservative and reliable option [3]. Turbine meters with accuracy of ±0.5% FSD or better and repeatability of 0.1% FSD are available, only it must to be ensured that it is of good quality and that the manufacturer has a track record of manufacturing turbine meters for cryogenic applications. Material selection for cryogens is also important. Normally, a stainless steel body with nickel, 17-4 PH rotor and ceramic ball bearing are common choices of materials, as indicated in Section 2.4.1 of Chapter V. Wide variations in operating temperature are available, e.g., (−) 448 to +450°F (−267 to 232°C) [7].

4.4.0 Vortex Meter in Cryogenic Applications

As discussed in Section 3.1.1 of Chapter V, when a shedder bar is placed in a flow, Karman vortices are generated on the downstream side of the bar. The Karman vortices are detected. The vortex frequency is proportional to the flow velocity. The vortex meter does not have any moving parts and so vulnerability due to low lubrication at cryogenic temperature is not applicable. No zero adjustments are necessary. In order to have lower pressure drop, a single shedder bar may be used. Vortex meters are susceptible to pipe vibration. In order to prevent measurements being influenced by noise due to strong piping, vibration may affect the accuracy of vortex frequency detection. In many instruments piezoelectric elements are installed to detect vibration to adjust the output, e.g., digital YEWFLO of YEL. Such signals are duly processed by digital signal processing (DSP). For cryogenic applications the operating temperature range could be from −200 to 40°C. Normally vortex meters are available with built-in temperature or RTD sensors (equivalent to Pt1000, Class A) for temperature monitoring function and a mass flow rate calculation

function. For this reason this meter is often referred to as a multivariable flow meter. Normally these meters are equipped with DSP, so as to calculate and provide outputs such as mass flow rate, temperature, pressure, volumetric flow rate, and fluid density. Such processing functions facilitate highly accurate measurement of flow rate over a wide range, even under radically fluctuating temperatures. An accuracy of 1.0% AR with repeatability 0.2% AR is possible in available meters.

4.5.0 Coriolis Mass Flow Meter in Cryogenic Applications

A Coriolis mass flow meter (refer to Section 2.1.0 of Chapter VI) consists of a manifold which splits the flow into two parallel tubes (commonly U shaped). The tubes are vibrated at a resonant frequency of the system. With passage of flow through the tubes, due to Coriolis force there will be a phase shift (Δt). The delta t is directly proportional to the mass flow rate. Coriolis meters are insensitive to fluid parameters (i.e., density, swirl, viscosity, etc.) and find their uses in a wide range of applications. A typical Coriolis meter makes a temperature measurement for compensation of the vibration characteristics of the sensing element. Proper account must be taken of the nonlinear temperature dependence of the Young's modulus of the vibrating tube in the Coriolis meter. As discussed earlier, the change in modulus of elasticity is well characterized, hence the modulus of elasticity can be corrected at various operating temperatures. Here it is important to note that the slightest warming can cause these fluids to flash, generating bubbles and causing measurement error. To save on cost, extra cooling below boiling point is normally avoided in the main system design. Therefore, it is critical to size the meter in such a way that sizing is optimum, and there is no extra pressure drop to cause flashing.

As already discussed, as the Coriolis meter directly measures mass and temperature, the effect on the vibration tube can be easily compensated for, so Coriolis mass flow meters in many ways are well suited for cryogenic fluids. However, it is possible that these cryogens and subzero fluids freeze the internal measuring components to create a restriction of meter motion and deterioration of measurement. It is essential that suitable materials must be selected for the sensor, the driver, and coil components for cryogenic operating conditions, i.e., performance and durability at cryogenic temperatures. In some meters, e.g., Rota*MASS* sensor, the interior space must be kept free of any air and by filling the meter with a dry, inert gas [8]. As already explained, unlike other flow-measuring techniques, Coriolis meters respond directly to mass flow, eliminating the need for density compensation. Also, Coriolis mass flow meters do not have the prerequisites for inlet flow conditioning, normally applicable for other meter types. In Coriolis meters absolute accuracy of better than 0.25% and reproducibility of 0.2% are easily achievable. Modern meters have digital signal processing (DSP) for better performance, e.g., Micro motion Elite sensor with multivariable DSP.

4.6.0 Ultrasonic Flow Meter in Cryogenic Applications

Noninvasive ultrasonic flow meters in cryogenic flow applications use the transit time method to determine flow through the pipe. There are two transducers at the opposite sides of the pipe line to measure the transit time, as already discussed in Section 6.1.0 of Chapter V. The arrangement is similar to that shown in Fig. V/6.1.0-2A. This transit time consists of the time taken by an ultrasound (US) signal to travel across the pipe and the time to convert an electrical signal into an acoustic signal. Temperature, especially cryogenic temperature, affects the accuracy of

measurement and would cause fluctuation in fluid flow, flow cell dimension, and acoustic characteristics. In order to compensate for this, most of the measurement systems also monitor the live temperature to provide compensation. Some use a waveguides system to concentrate the US signal into the fluid. These noninvasive ultrasonic flowmetering systems are well suited for LNG and other cryogenic applications at temperatures down to −200°C. These meters are available in various sizes to cater for the highest flow rates of loading/off-loading processes, as well as very low flow rates at the start or end of operation. The major features of these (same US measurement types described in Chapter V) types of measurements include but are not limited to the following:

- Noninvasive type;
- Highly reliable;
- Cost does not increase with line size;
- Easier to install;
- Cater to a wide variety of cryogenic fluids;
- Safe measurement;
- No pressure drop;
- No chances of leakage—no gaskets, no leakage points;
- Practically maintenance-free;
- No pipework modification;
- Dual beam monitoring possible.

4.7.0 Processing Electronics in Cryogenic Applications

High performances of the meters have been made possible due to the use of multivariable transmitters and processing electronics. Modern high-precision digital signal processing (DSP) accurately processes field-acquired data to produce desired outputs with the help of advanced software and embedded microcontrollers. Most of the new advanced technological developments in electronics bring about good solutions in cryogenic measurements. Advanced communication, graphical display, and operator interface with "soft keys" allow for easy interaction between the operator and the instrument. The operator interface has been made easy with the help of multiple easy-to-follow messages in multilingual message forms. These advanced interactions help navigate through the instrument menu which may be in hierarchical format. The advanced computation algorithms calculate the volume, mass, and density of the fluid. Extensive built-in diagnostics systems find faults immediately. Diagnostics includes but is not limited to factory setting tests and has factory test mode, troubleshooting, serial interface testing, etc. Many of the functions are password/authentication protected. The displays can be volumetric/mass flow (either direct measured or computed) and total flow. The reset of the total flow is normally possible only by an authorized person through the use of a password and such deletion details are recorded. High-speed DSP ensures accuracy under the toughest conditions of high noise, high turndown, etc. Computation capability for concentration and net flow measurement eliminate the need for additional instruments. These features are found in micromotion MVD transmitters and DSP. Displays can be in backlit LCD or LED with an incremental rate as low as 100 ms. Most of these electronic processing units support necessary communication links and connections, such RS 485, HART, and/or various kinds of fieldbus systems for system communication and integration. In conclusion it can be argued that, behind the success of high-performing meters in cryogenic flow meters, lies the powerful processing capabilities of DSP and handling multivariable data.

There are not too many independent laboratory-based cryogenic flow meter calibration facilities in the world. To the best of the author's knowledge, only one independent laboratory for

cryogenic flow meter calibration is in existence. Thus these flow meters are normally calibrated with water at ambient conditions. This therefore brings major uncertainty in transferring laboratory calibrations using water to other cryogenic liquids, including LNG, for which long-term custody transfer and fiscal calculations are necessary. Therefore it is recommended to get the meter tested in an independent laboratory for precise measurements.

The discussions on cryogenic flow measurement thus come to an end and we now look into local flow meters or flow gages.

5.0.0 FLOW GAGES

Normally, flow meters which are used for local flow monitoring are referred to as flow gages. Flow gages usually have local indications in the form of a dial or digital readout. In some cases there may not be any reading, e.g., flow/no-flow gages—sight flow indicator. Generally flow gauges work without any external power supply. However, digital flow gages, i.e., flow gages with electronic digital displays, do require power. So, with the requirement for power supply, flow gages cannot be distinguished from normal flow meters. Normally these local gages do not have remote signal transmission facilities, but some may have built-in contact with them. Another distinguishing issue could be lower performance of flow gages when compared with flow meters. There are several categories of flow gages which are discussed in this section. Different manufacturers employ different design criteria, which change from one to another, but the basic concept of flow gauge operation depends solely on the principle of dynamic pressure [9]. There are several categories of flow gages. Some use DP gages to measure the flow in the pipe. Some gages have digital displays and some have a simple sight flow indicator which indicates flow/no flow condition without any flow reading. There is another kind of flow gage which basically is a flow meter with a local totalizer without remote transmission facility. These are mainly used as oil meters and water meters. These are also categorized here. In this section brief discussions on different flow gages have been enumerated.

5.1.0 Direct-Flow Gages

From the discussion on head type flow meters it is understood that when a designed restriction is placed in the conduit, there will be a pressure drop across it. Based on Bernoulli's theorem on energy balance, flow in the conduit can be computed or related to the pressure drop across the designed restriction. So, when DP is measured across the restriction it arrives at the flow. The dial is calibrated in terms of flow through the pipe.

5.1.1 DESCRIPTION OF DIRECT-FLOW GAGES

Direct flow gages are direct reading flow meters with easy-to-read dials of different sizes. The dial is calibrated in terms of suitable flow engineering units, such as GPM/Lit/min. These gages are normally fabricated aluminum. These direct reading gages do not require external power and have a clear scale and pointer reading. These gages measure the flow based on the differentials created by a built-in calibrated Venturi/nozzle or integral orifice as shown in Fig. X/5.1.0-1A and B. These meters read the differential pressure across the built-in flow element. Since these meters are calibrated under standard atmospheric conditions, gages normally are supplied with reference flow charts. Direct flow gages are available for water, oil, and many other viscous fluids without deposition. The range of fluids covered depends on the flow gage type and associated flow element. These gages are also applicable for gases such oxygen, compressed air, nitrogen, etc. These are also used in-process steam lines.

There are a variety of gage offered by the manufacturers. Some even offer provision for remote signal transmission also. Based on applications, variations in pressure drops have been shown in Fig. X/5.1.0-1C. Curve B is applicable for high-pressure applications and for materials like SS. Curve A is applicable for materials like bronze.

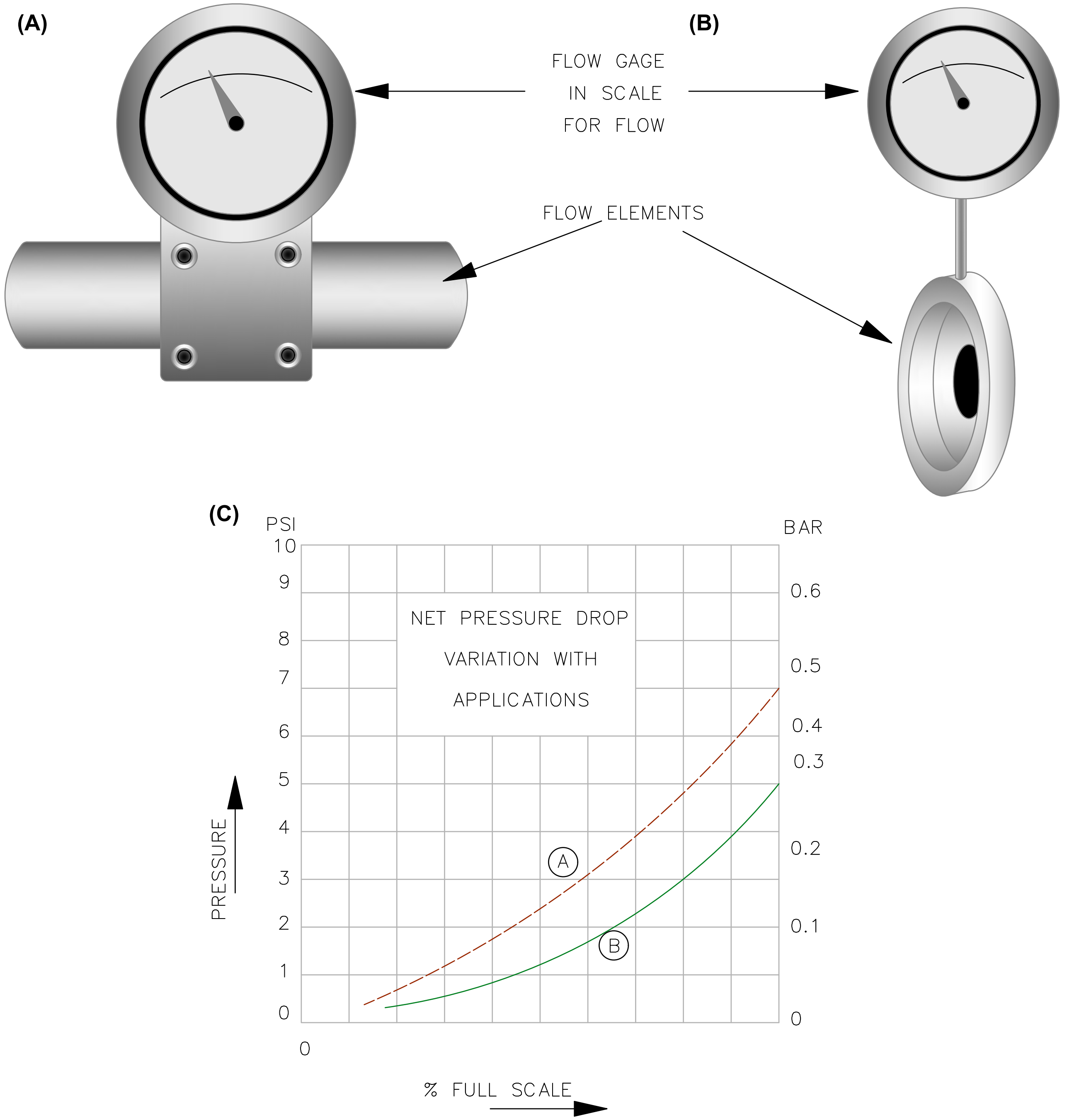

FIGURE X/5.1.0-1 Direct flow gage. (A) Flow gage with Venturi. (B) Flow gage with orifice. (C) Pressure drop characteristics.

5.1.2 FEATURES AND APPLICATIONS OF DIRECT-FLOW GAGES

Some of the noteworthy features and applications are noted here:

1. **Features:** The following features are normally noted in direct-flow gages:
   - *Flow element:* Flow element selections are based on the pressure loss allowed. Venturi type offers less pressure loss;
   - *Reading:* Easy to read direct flow through transparent front plastic/glass;
   - *Indication:* White background with black graduation for scale with pointer;
   - *Housing:* Durable aluminum housing;
   - *Size:* 100 mm standard size, other sizes are also available;
   - *Scale:* 270 degrees analog scale;
   - *Accuracy and range:* Accuracy of 1% FSD possible in span ration 5−6:1.
2. **Application:** There are a number of applications including the following:
   - Filter monitoring;
   - Limited slurries and liquids with suspended solids;
   - Turbine and other machine lube oil delivery monitoring;
   - Heat exchanger coolant/steam delivery monitoring;
   - Compressed air system;
   - Cutting oil flow in automatic machines.

5.1.3 SPECIFICATION FOR DIRECT-FLOW GAGES

A brief specification of direct-flow gages has been enumerated in Table X/5.1.0-1.

TABLE X/5.1.0-1 Specification of Direct Flow Gage

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid types	Various liquids like water, oil, lube oil air/gases including natural gas, compressed air, process steam, some limited: slurries, liquid with solids		
2	Pressure limit	Normally within 1.5 bar		
3	Over pressure	Normally >1.5 times, some are provided with over pressure protection		
4	Line size	½″ (12) to 3″ (80) but sizes up to 8″ (200)		
5	Temperature	−5 to 75°C		
6	Orientation	Vertical, horizontal; some with diaphragm, meant for vertical position		
7	Connection	Threaded, NPT/BS of different sizes 1/2″ or 3/4″ sizes are common		
8	Flow element	Venturi, nozzle, or integral orifice		
9	Sensor material	Stainless steel SS 316		
10	Casing/housing Material	Aluminum housing with plastic/glass dial		
11	Seal Material	Viton/EPR/PTFE		
12	IP Cl Ass	IP 65 possible		
13	Accuracy	±1 FSD		To specify
14	Application of interest	See Subsection 5.1.2.2 above		
15	Optional	Alarm contact of rating 30 V 1 A Remote transmission (4−20 mADC) or digital readout power supply if necessary 24 VDC		

Continued

TABLE X/5.1.0-1 Specification of Direct Flow Gage—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
16	Accessories	Mounting kits and fittings, power supply digital readout as specified		
17	Special feature	To specify		

We now look into another commonly used flow gage popularly known as the sight flow indicator, which is mainly used for flow/no-flow detection locally.

5.2.0 Sight Flow Indicator

Matching with the name, sight flow (SF) indicators display flow or contents of pipelines. As indicated earlier SF indicators are mainly meant for viewing flow, i.e., for detection of flow. There are several types of local flow gages that fall under this category. However, in some cases there are meter types where, in addition to viewing flow, local indications and even contacts are available for low/no flow. There are several types of sight flow indicators available and some of these are depicted in Fig. X/5.2.0-1. These are other types also but they are very similar with

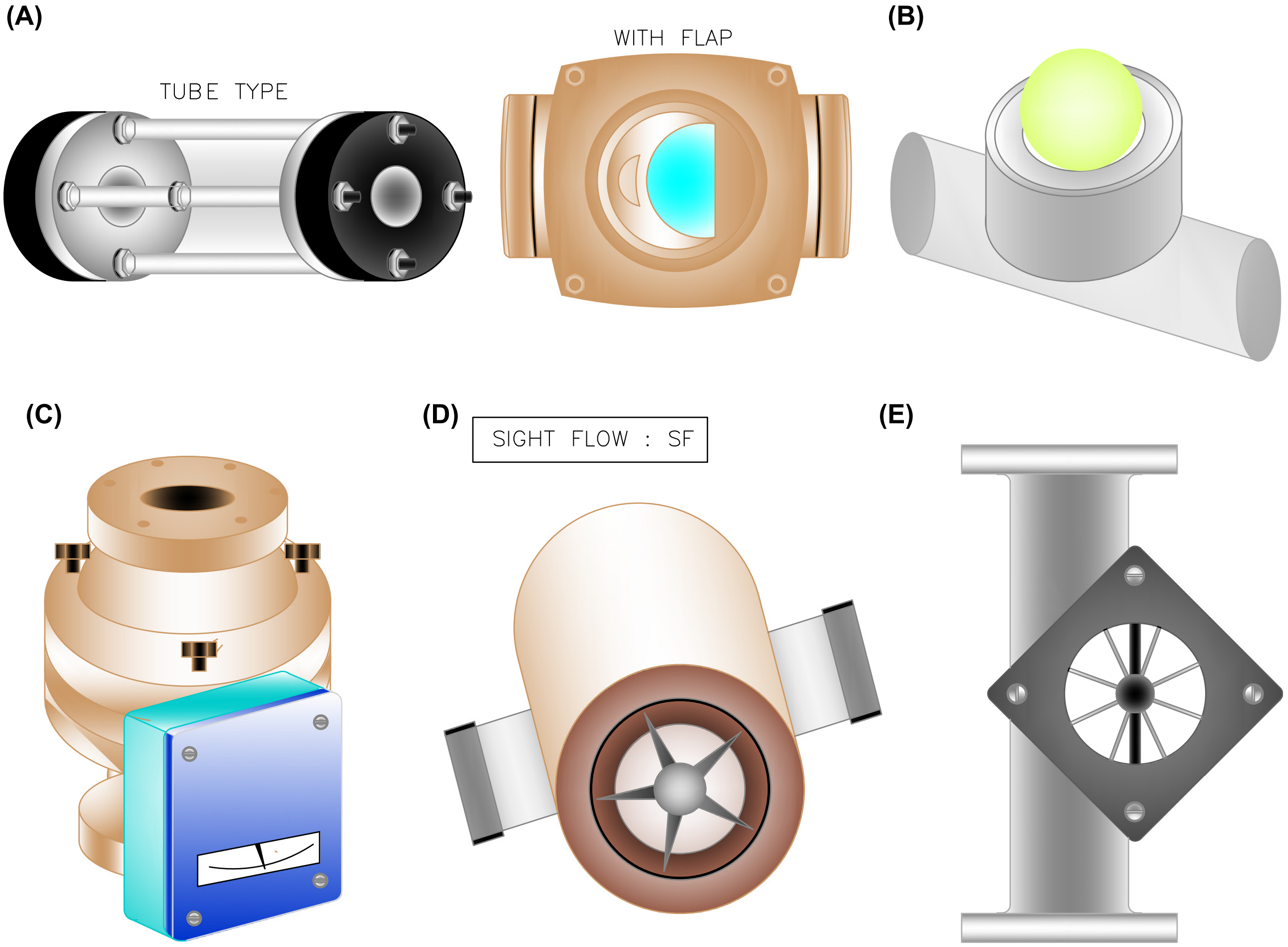

FIGURE X/5.2.0-1 Sight flow (SF) indicator types. (A) Standard SF indicator. (B) SF indicator with ball. (C) Flow rate type. (D) Impeller type. (E) SF with spinner.

little modification and addition of various options, such as output contacts, etc. Also, it is worth noting that sight flow indicators are available also with liners for corrosive fluids.

In this section a few types are discussed one by one. The discussions start with the tube type.

5.2.1 TUBE TYPE SIGHT FLOW INDICATORS

This type is simply a piece of tube of transparent material through which the fluid passes and the flow is visible from outside, purely for a confirmatory flow or no-flow signal. A typical straight type has been shown in Fig. X/5.2.0-1A (left). This can be used for lube oil lines but may not be suitable for transparent liquids like water. The tube diameter should be the same as the main pipeline, so that there is no pressure loss. There are two options: one straight type and one angular (viewing at right angles to the flow direction). The main disadvantage is that it has joints made by exerting on it. A brief specification is enumerated below:

1. **Sizes available:** 12 mm (1/2″) up to 150 mm (6″);
2. **Body material (angular):** Cast iron (200°C)/ CS or SS (250°C);
3. **Cover (angular):** MS;
4. **Viewing glass:** Borosilicate glass;
5. **Fastener:** MS;
6. **End connection:** Flanges (RF/FF) of CS or SS (250°C): ANSI 150 lb or equivalent;
7. **Gasket:** PTFE;
8. **Pressure rating:** Normally 3 barg for straight type and about 20 barg for angular type.

Very similar to this is the flat type discussed below.

5.2.2 SIGHT FLOW INDICATOR WITH FLAP

These are low-cost sight flow indicators, these are also a straight through indicator with a sprout. They are available with a flap and scale to indicate flow. A typical SF indicator has been depicted in Fig. X/5.2.0-1A (right). A short specification of the same has been enumerated below:

1. **Available sizes:** 12 up to 80 mm;
2. **Pressure:** Up to 10 barg;
3. **Temperature:** Around 200°C;
4. **Scale:** Scale when provided, show flap position which is calibrated in terms of flow;
5. **Body:** Stainless steel (casting quality CF8M);
6. **Flap:** SS316;
7. **Cover (angular):** MS;
8. **Viewing glass:** Borosilicate glass;
9. **End connection:** Screwed of different sizes (NPT/BSP) or flanges (RF/FF) of CS or SS (250°C): ANSI 150 lb or equivalent;
10. **Gasket:** PTFE.

5.2.3 SIGHT FLOW INDICATOR WITH BALL/SPINNER

A typical SF indicator of this type is shown in Fig. X/5.2.0-1B. The flow is indicated by a ball or spinner. They are used for plant protection applications with local indication of flow, such as coolant/oil to plant machinery.

A short specification of the same has been enumerated below:

1. **Available sizes:** 10 up to 80 mm;
2. **Pressure:** Up to 16 barg;
3. **Temperature:** Around 150°C;
4. **Body:** Stainless steel (casting quality CF8M)/gun metal;
5. **Ball/spinner:** Nylon/PTFE;
6. **Cover:** MS;
7. **Viewing glass:** Borosilicate glass;
8. **Gasket:** Nitril O ring;
9. **End connection:** Screwed of different sizes (NPT/BSP);
10. **Gasket:** PTFE.

5.2.4 SIGHT FLOW INDICATOR WITH SPINNER

A typical SF indicator of this type is shown in Fig. X/5.2.0-1E. The flow is indicated by a spinner. This is a double-sided indicator [10] and

is practically a modified version of the one discussed above. This type can be used for vacuum services also. A short specification of the same has been enumerated here:

1. **Available sizes:** 10 up to 150 mm;
2. **Pressure:** Vacuum to 16 barg [10];
3. **Temperature:** Up to 250°C possible;
4. **Body:** Gun metal/cast iron/carbon steel (A216 WCB)/stainless steel (casting quality CF8M)/ gun metal;
5. **Spinner:** SS, other material also possible;
6. **Cover:** MS;
7. **Viewing glass:** Borosilicate glass;
8. **Gasket:** PTFE;
9. **End connection:** Screwed of different sizes (NPT/BSP), flange ANSI 150 lb or equivalent.

5.2.5 SIGHT FLOW INDICATOR—IMPELLER TYPE

A typical SF indicator of this type is shown in Fig. X/5.2.0-1D. These are available in double or single viewing glasses.

A short specification of the same has been enumerated here:

1. **Services:** Gas/liquid [11];
2. **Available sizes:** 10 up to 80 mm;
3. **Pressure:** Vacuum up to 10 barg [11];
4. **Temperature:** Up to 100°C possible;
5. **Body:** Bronze/carbon steel/stainless steel (casting quality CF8M)/others;
6. **Spinner:** SS, other material also possible;
7. **Viewing glass:** Borosilicate glass;
8. **Gasket:** PTFE;
9. **End connection:** Screwed of different sizes (NPT/BSP), flange ANSI 150 lb or equivalent.

5.2.6 FLOW RATE TYPE INDICATOR

This type really is not commensurate with its name, but is discussed here because this one also make use of a similar technique as used in the other types discussed. These types of gages have a mechanical indicator on a dial. Optionally they are provided with suitable contact output. They are available with a wide range of flow and a wide range of meter specifications. These are available from sizes ½″ to 8″. There are varieties of sensing possible using swing vane, flow piston, and variable orifice types. Some of these are supplied with a power supply and can give remote transmission facility. Since this section is mainly on local indications, this has been discussed with other mechanical flow meters in Section 6.2.2 of this chapter.

With this the discussions on sight flow indication come to an end and we now investigate digital display type local flow gages.

5.3.0 Digital Local Flow Indicator

These types of meters are electronic type small flow meters. They are installed either in-line or at the end of a hose. The large easy-to-read display and compact lightweight design makes it easy to handle. These meters work on paddle wheel flow-metering principles with a suitable flow sensor. Most are microprocessor-based meters with provisions for battery backup. The majority of these meters can display both the rate flow and the totalized volumetric flow locally. Totalized flows can be resettable/nonresettable types. Some also offer the facility to control batch operations. They are mainly used for oil and water metering. In oil metering it is very handy, and is installed in a fuel transfer pump for oil delivery system. They are mainly made up of aluminum housing and are quite durable. Such water meters find their uses in domestic as well as industrial applications, such as greenhouses, small plant process water supply, cement mixing machines, and pond water supply lines. Some of these meters also offer remote transmission facility.

5.3.1 FEATURES OF DIGITAL LOCAL FLOW METERS

Some typical features of this type of flow meter are enumerated below:

1. **Ranges available:** 0−>750 L/s;
2. **Construction:** Rugged construction;
3. **Application:** Indoor/outdoor;
4. **Battery Backup:** provided;
5. **Totalizer reset:** Possible;

6. **Batch control:** Possible [12];
7. **Display:** Rate and/or totalized;
8. **Display size:** Tall display;
9. **Batch size:** Six digit up to 999,999.

5.3.2 SHORT SPECIFICATION OF DIGITAL LOCAL FLOW METERS

Local digital flow meter specification details have been enumerated here:

1. **Flow range:** Depending on size up to 800 Lpm;
2. **Sizes:** Available in various sizes from 12 to 50 mm /80 mm;
3. **Maximum pressure:** Up to 20 barg;
4. **Maximum temperature:** 60°C;
5. **Housing material:** Aluminum/cast steel;
6. **Wetted part materials:** Aluminum, Nitril, steel [12];
7. **Electronics housing materials:** ABS;
8. **End connection:** Threaded normally, NPT/BSP;
9. **Display:** Rate flow and/or totalized;
10. **Display type and size:** Backlit LCD/LED;
11. **Display size:** 10−12 mm [12];
12. **Reset:** Possible in some cases;
13. **Control:** Batch control possible;
14. **Accuracy:** Around ±1% AR.

There are a few other kinds of flow meter which are basically mechanical meters with local mechanical readings for flow rate as well as totalized flow. Many of these meters also have provision for electrical transmission facilities. Therefore, these cannot be treated as simple local flow gages. The main use of these meters is as a water meter. They have several built-in working principles such as Woltmann metering and rotary piston principles. Some fuel meters based on PD metering also come under this heading. These are treated separately in the next section.

6.0.0 MECHANICAL TYPE FLOW METERS

In this section discussions are presented on a few mechanical type flow meters which are used for mechanical totalizing fluid flows. Some of these meters have provisions for electrical remote transmissions and can also show the flow rate. They are mainly used as water flow meters and fuel flow meters. Woltmann type flow meters discussed in Section 2.9.2 of Chapter V are mainly used as water meters, and are used as irrigation and agriculture water meters, and fertilizer meters used for fertilizer and chemical solutions. On the other hand, rotary piston principles discussed in Section 5.1.1 of Chapter IV are used for domestic water meters and some industrial water meters. The other category is fuel meters, which are mainly based on PD meter principles. These meters are used for measuring oil receipt and oil consumption.

6.1.0 Mechanical Water Meters

As indicated above, most of these flow meters are Woltmann flow meters (discussed in Section 2.9.2 of Chapter V). There are several categories of these meters, these are domestic water flow meters, industrial water flow meters, irrigation and agricultural water flow meters, and fertilizer flow meters. Many data and details presented here are based on data from Kent Water Meters [***courtesy of Kent Water Meters***]. The discussions start with general design details of these water meters.

6.1.1 GENERAL DESIGN DETAILS FOR WATER METERS

Some of the standard features and design details available for water meters are briefly discussed below. These are generalized in nature.

1. **Standard construction features:** For domestic and industrial water flow, meter working based on a rotary piston has a grooved piston to reduce stoppages and to ensure durability. Good engineering practices are adapted to make the system leak-proof. For irrigation, agricultural, and fertilizer meters Woltmann flow metering principles are used. Advanced engineering plastics are often used for

measuring chambers, e.g., the V100 Kent meter. Suitable seals are used between the measuring chamber and the meter body as discussed in Chapter IV. Woltmann meters used for irrigation and agriculture, as well as for fertilizer water meter designs, should be such that there will be negligible loss of head and they should be simple to maintain. These meters are now available with the possibility for a field-replaceable measuring unit. Registers are available as hermetically sealed units. Mechanical registers are offered with a totalizer, three pointers, and a leakage detector. In fertilizer water meters, plastic constructions are used to avoid corrosion.

2. **Register:** The register is fully sealed and vacuum-filled [13]. A number of rollers are immersed in a nontoxic liquid to act as lubricant. The register is placed in a window to give clear readings, and in some cases these are provided with a window lens.
3. **Tamperproof:** Since the meters are used for billing purposes, features are included in the meter to resist illegal tampering by not allowing disassembling during operation.
4. **Remote reading:** These meters have provision for remote signaling/transmission. Some have a built-in remote transmission facility and also facilities for remote reading. It is even possible in some meters to be interrogated by a PLC or a computer. As applicable, pulse signals are the normal outputs from the meter.
5. **Reverse flow:** In most of cases reverse flow metering is possible to facilitate information and network management and revenue billing applications. Depending on applications there can be an internal disc-type reverse-flow restrictor to eliminate water from flowing back illegally.
6. **High performance:** For better meter performance, systems incorporate necessary design, e.g., grooved rotary piston in water meters.
7. **Management tool:** In order to carry out effective management, such as consumption and flow, etc., many meters are available with the necessary management information tool supports.

Now the discussions move on to standard domestic portable water and industrial water meters.

6.1.2 DOMESTIC WATER FLOW METERS

Domestic water flow meters offer working on rotary piston normally offering the desired accuracy with tamper-proof operation. It is also possible to get remote readings. These are available in various sizes. A typical domestic water flow meter based on the Kent meter is depicted in Fig. X/6.1.0-1. Normally these are available with a cover lid as shown in the left-hand side of this figure. Details of the top dial of the meter are illustrated on the right-hand side of the figure. The dial shows flow directions, a pointer for bidirectional communication, 6–7 digit register, and unit selection with bidirectional pulse communication facility.

The discussion starts with some features of the meter.

1. **Features:** The following are a few features worth noting:
   - *Principles of operation:* Rotary piston principles (see Section 5.1.1 of Chapter IV);
   - *Accuracy:* Desired accuracy and performance in any position;
   - *Durability:* Grooved piston for better durability;
   - *Tamperproof:* Tamperproof construction and operation;
   - *Sizes:* Available in sizes up to 250 mm size;
   - *Pressure rating*: Pressure up to 16 barg at temperature up to 50°C;
   - *Output:* Inductive pulse output with multiple pulses to support management information;
   - *Reverse flow:* Bidirectional flow measurement possible;
   - *Register:* Built-in mechanical register;
   - *Readability:* Clear readability;
   - *Calibration:* Some meters do not require calibration throughout life span [13];
   - *Special feature:* Exceeds Class B specification in forward direction and for sizes up to 150 mm in reverse direction [14].

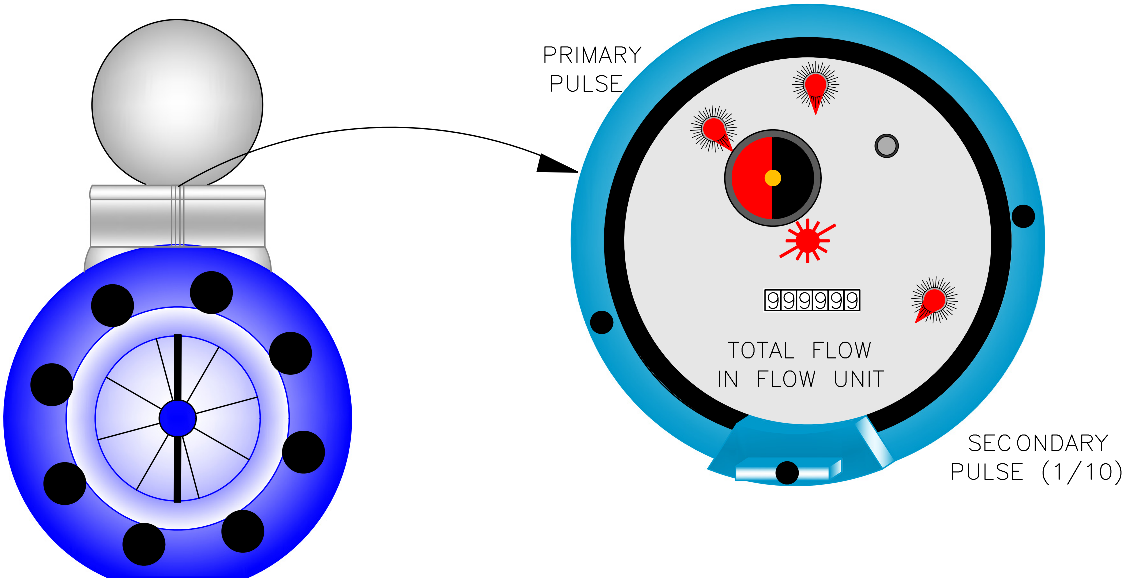

FIGURE X/6.1.0-1 Domestic water meter. *Developed based on Kent meter. Courtesy: George Kent.*

2. **Specification:** A brief specification for a domestic/industrial water meter is given in Table X/6.1.2-1. It is always recommended to use a net strainer for protection of the meter. There is a wide variety of this meter available in the market. The specification given covers the general technical data and the best-known technical data. Data furnished here have been taken from various models of reputed makes.

TABLE X/6.1.2-1 Specification for Domestic Water Meter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Meter size	Various models with sizes from 12 to up to 300 mm		
2	Flow range	1.5–1000 m^3/h		
3	Overload flow range	Generally twice the flow range		
4	Pressure limit	Normally within 16 barg		
5	Temperature	Normally 50°C		
6	Register	Normally million m^3. In 6–7 digits		
7	Head loss at overload flow	84–21 KPa, as the meter size increases head loss decreases		
8	Body material	Copper alloys are common		
9	Measuring chamber	Polystyrene/plastic		

Continued

TABLE X/6.1.2-1 Specification for Domestic Water Meter—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
10	Rotor	Polyamide		
11	O ring	Elastomer		
12	Orientation	Vertical, horizontal; some with diaphragm, meant for vertical position		
13	Connection	Threaded, NPT/BS of different suitable sizes. Flange connections for higher sizes are also possible		
14	Output	Pulse output		
15	Pulse rate	Variable normally litter per pulse		
16	Primary pulse	For bidirectional flow; two wire connection; one wire carries pulse and the other for direction flag		For Kent meter Courtesy: Kent meter
17	Secondary pulse	Two-wire connection; one-wire pulse compensation; other flag to indicate compensation process		For Kent meter Courtesy: Kent meter
18	Accuracy	2% average		

6.1.3 IRRIGATION, AGRICULTURE AND FERTILIZER WATER FLOW METER

Woltmann type meters used for irrigation, agriculture, and fertilizer purposes are discussed in this section. It is to be noted that here fertilizer meter means a kind of water meter for fertilizer/chemical dosing purposes, i.e., a fertilizer for agricultural applications. A typical mechanical water meter (fertilizer) is shown in Fig. X/6.1.0-2.

The display part is similar to that in the domestic/industrial water flow meter shown above. The discussion starts with features of a Woltmann water meter.

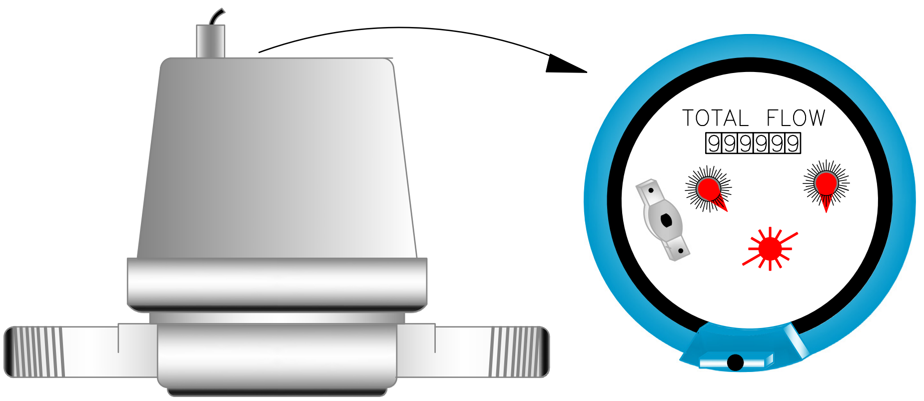

FIGURE X/6.1.0-2 Mechanical water meter (fertilizer). *Developed based on Kent meter. Courtesy: George Kent.*

1. **Features:** The typical features of this type of water meter are enumerated here:
   - *Loss:* Low-loss meter;
   - *Replacement*: Field-replaceable measuring chamber;
   - *High-flow condition:* Possible to cater to high flow rate;
   - *Harsh environment:* Ability to cater to harsh environmental conditions with high humidity and vibration;
   - *Corrosion protection:* Corrosion-resistant plastic components when necessary;
   - *Register:* Mechanical register with totalizer, three pointers, and leakage detector;
   - *Hermetical seal:* Hermetically sealed register;
   - *Readability:* Easy readable register with lens;
   - *Rate flow:* Rate flow indication possible;
   - *Wide range and accuracy:* Possible for accuracy curve to cover wide range based on ISO standard.
2. **Specification:** A brief specification for Irrigation agriculture and fertilizer water meter is given in Table X/6.1.3-1. It is always recommended to use an in-net strainer for the protection of the meter. There is a wide variety of meter available in the market.

TABLE X/6.1.3-1 Specification for Irrigation Agriculture and Fertilizer Water Meter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Meter Size	Various models with sizes: Plastic fertilizer meters: 12–25 mm. Water meters: 40–250 mm		
2	Flow range	Water meter: 50–7500 m^3/h Fertilizer: 0.6–6 m^3/h		
3	Overload flow range	Generally nearly (less than) twice the flow range		
4	Pressure limit	Normally within 13 barg		
5	Temperature	Normally 60°C		
6	Register	Normally million m^3. In 6–7 digits		
7	Register connection	Magnetic coupling for register		
8	Head loss at overload flow	Varies with meter type; data sheet to be consulted		
9	Orientation	Any position: Horizontal/vertical		
10	Body material	Fertilizer meter: Organic polymer; polyphenylene sulfide (PPS) Water meter: Polyester-coated cast iron/brass		
11	O ring	Elastomer		
12	Standard	ISO4064/EEC		
13	Connection	Threaded, NPT/BS of different suitable sizes. Flange connections ISO standard		
14	Output	Optional electrical outputs possible		
15	Electrical output options	Rate flow and volume flow as well as electrical contact output		
16	Accuracy	2% AR (average)		
17	Accessories	Filter at upstream		

The specification given covers general technical data and the best-known technical data. The data furnished here have been taken from various models of reputed makes.

6.2.0 Mechanical Oil and Other Flow Meter

Mechanical flow meters with a local totalizer and/or rate indicators find their applications in oil flow measurement. There are a few other mechanical flow meters with local-scale pointer indicators available for various applications. In this section these shall be discussed.

Oil consumption and oil receipts are quite important in this respect. The discussion starts with oil meters.

6.2.1 MECHANICAL OIL FLOW METERS

In the modern world, on account of more and more energy consumption, fuel price is in a rising trend. Therefore, it is needless to say that monitoring of fuel at each stage is always crucial. A typical oil flow meter and its application are depicted in Fig. X/6.2.1-1.

1. **Oil receipt monitoring:** Petroleum products, such as diesel, LSHS, and furnace oil are all

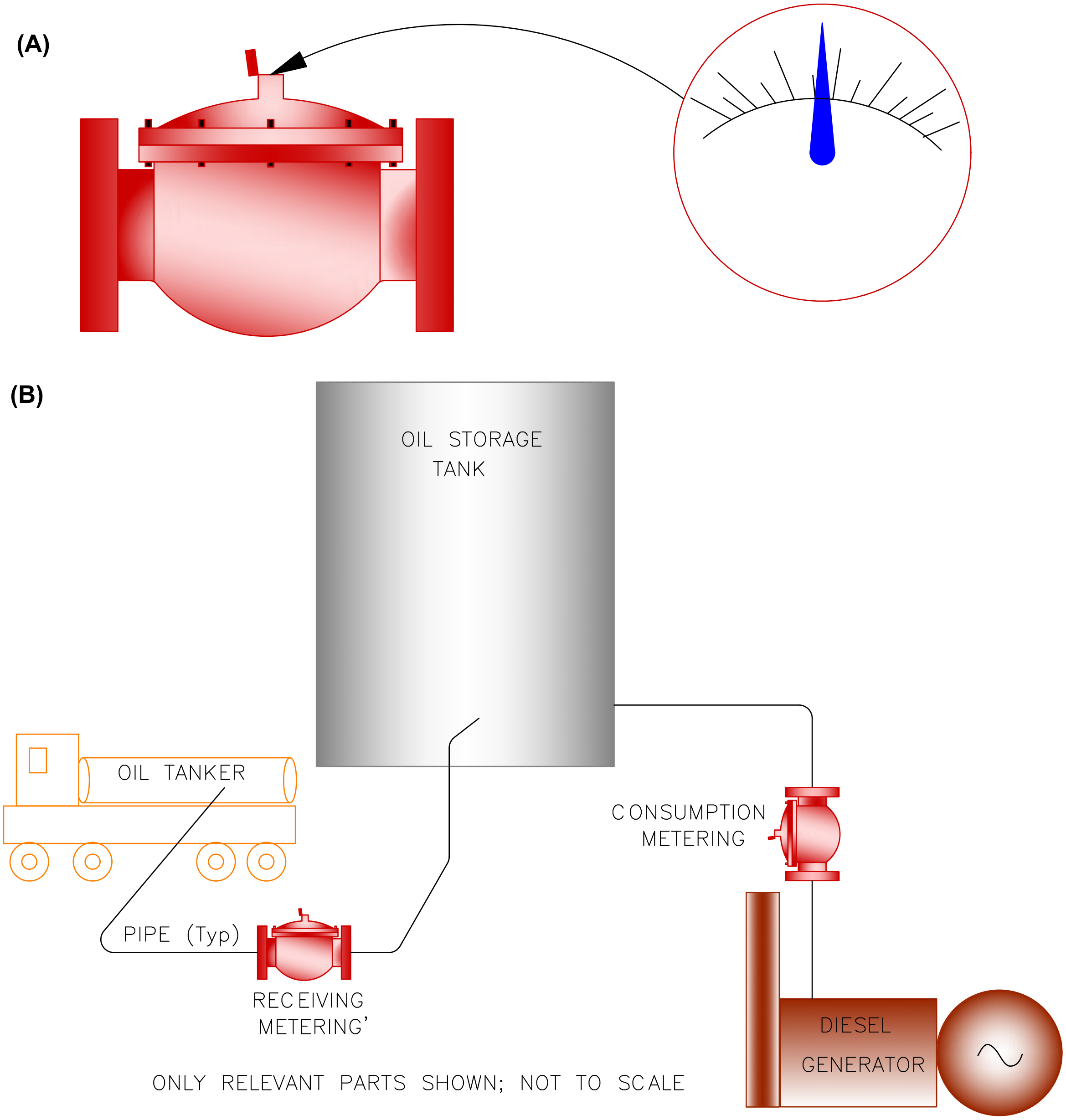

FIGURE X/6.2.1-1 Oil flow meter. (A) Oil meter details. (B) Application of oil meter.

received in plants or oil depots by tankers or by railways and tanks that are filled by pipeline. In most earlier cases oil receipt was measured by dipsticks in the tank. This is not only a very crude way of measuring the quantity but there is the possibility of pilferage by unscrupulous personnel. In modern times people use an oil flow meter to monitor the quantity of oil delivered. Therefore, the actual oil receipt can be accounted for. In this connection, Fig. X/6.2.1-1 may be referenced.

2. **Oil consumption:** As petroleum products are very costly it is important to account for the quantity of oil consumed by various users, such as diesel generators, boilers, and hot air generators. In such applications people have started deploying these kinds of oil meter. Boilers, etc. mentioned here are small units, for larger units or for utility boilers regular electronic PD meters are used. In this connection, Fig. X/6.2.1-1 may be referenced.
3. **Features:** The major features of these meters are as follows:
   - *Principles:* Simple rotary piston principle;
   - *Components:* Least possible number of components;
   - *Register:* Register magnetically coupled;
   - *Pressure loss:* Low line pressure loss;
   - *Quality:* Reliability and accuracy;
   - *Output:* Electrical output.
4. **Specification:** A brief specification of an oil meter is given in Table X/6.2.1-1

TABLE X/6.2.1-1 Specification for Oil Flow Meter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Meter size	15–80 mm		
2	Flow range	0.01–50 m^3/h		
3	Fluid types	Petroleum products, such as MS, HSD, LDO, LSHS, etc.		
4	Viscosity	<1000 cP		
5	Pressure limit	Normally within 40 barg		
6	Temperature	Normally 150°C		
7	Register	Normally million m^3. In 6–7 digits		
8	Register connection	Magnetic coupling for register		
9	Head loss at overload flow	Actual data sheet and loss chart to be consulted		
10	Orientation	Any position: Horizontal/vertical		
11	Body and working chamber material	Brass/bronze, cast iron		
12	Piston material	Aluminum		
13	O ring/gasket	Viton/special compound		
14	Standard	ISO4064/EEC		
15	Connection	Threaded, NPT/BS of different suitable sizes. Flange connections ISO standard		
16	Output	Optional electrical outputs possible		

Continued

TABLE X/6.2.1-1 Specification for Oil Flow Meter—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
17	Accuracy	0.5% AR average		
18	Accessories	Filter/air release at upstream		Refer to Chapter IV

6.2.2 OTHER MECHANICAL FLOW METERS

There are a few other mechanical flow meters, as shown in Fig. X/5.2.0-1C. These meters are basically rate flow indicators. In these meters flow rates are indicated in a dial with the help of a mechanical pointer. These are mechanical flow meters with a wide range of sizes, from 12 to 150 mm size. These meters also provide contact output and can act as a flow switch to be operated at a specified set point. Optionally these meters are provided with an electrical supply to give electrical outputs for remote transmissions and for batch and other controls. These meters operate in vane displacement mode. A tapered needle passing through an orifice in the face of a piston completely seals the port. When there is flow, the piston is displaced against a differential pressure/spring load and moves over the tapered section of the needle. Flow is allowed through the orifice. The tapered section is meant to cater to the changes in viscosity and flow variations. On account of the vane (spring-loaded) displacement there will be a variable orifice for variable flow for a specified viscosity value. Therefore, vane displacement is proportional to flow rate. These meters do not demand any upstream straight length for their operation. They can operate in pressure as high as 140 barg. Any kind of meter orientation is allowed. These are available in a wide range of body and vane materials to cater to a wide range of fluids. They are available with screwed end connections and are used in water treatment plants, synthetic base oils, corrosive fluids, paints, and solvents.

With this, the discussions on local flow gages/meters come to an end and we now investigate the flow switch types available and their applications.

7.0.0 FLOW SWITCH

In order to monitor flow in the conduit, flow switches are used. Here the word “monitor” actually refers to a broad spectrum in the sense that such monitoring could be local and remote. The local monitoring function could be met by the simple flow gages discussed above. Remote monitoring again could be continuous monitoring by indication, recording, etc. Alternatively, it could be when the flow in the conduit goes beyond a set value that some action is initiated. Most plants now operate remotely, therefore, such flow-monitoring devices should be field-mounted for initiating a remote action. Here, the word beyond has been used intentionally to mean that when flow goes below the set point action is to be initiated or when flow goes above a set point, action is to be initiated. Also, there are applications where flow is to be kept within a band (as seen in a batch process) using two such monitoring devices. The word “action” mentioned above could be a simple alarm, interlock, and/or tripping of equipment and/or a (sub) system. In such actions all the time flow trends are not always necessary. Therefore, a costly continuous monitoring (indicating/transmitting) type flow meter may not be necessary. From the above discussions it transpires that all instruments which can measure flow can also be used as flow switches, e.g., initiating contact for such action

discussed above could be obtained by using a simple limit value monitor (which could be a hardware device or could be software action from DCS/PLC). However, at times this is a costly proposition, e.g., providing a flow transmitter and limit value monitor in a lube oil line for a big pump/fan is too costly and there could be space constraint in the lube oil skid also. So, if only flow monitoring (that it is within the set point) is required for a particular application, the deployment of indicating or transmitting devices cannot be economically justified and at times due to space constraints cannot be accommodated also. This is where a *flow switch* is useful. Flow switches are used to monitor the line flow to determine if the flow rate is beyond a certain value. This specific certain value is referred to as the set point. Depending on the application, this set value could be fixed or adjustable. Most of the process switches offer adjustable set points. On reaching the set point (in rising/falling mode) like other process switches, the flow switch needs to respond by actuating an electric or pneumatic circuit. Electric flow switches (of interest here) need to actuate a set of contact(s). On reaching the set point when the flow switch is actuated, contact(s) configuration will stay in that state until the flow rate moves back from the set point. Let us take a specific case; when the flow is above x set point it will actuate. So when flow goes above x set point, e.g., NO contact closes. It remains closed as long as flow >x. However, it will be seen that it stays in that condition even if flow goes below x set point up to a certain value. This difference between the *set point* and the *reactivation point* is called the switch *differential* [15]. Next we define a few terms which will be frequently referred to and are applicable not only for flow switches but for process switches in general.

7.0.1 DEFINITIONS AND TERMINOLOGIES WITH EXPLANATIONS

The following terminologies are frequently used and it is important that these terms are well understood. It is recommended to refer to Section 1.2.1 of Chapter I also, for further understanding. These terms have been explained in Fig. X/7.0.0-1.

1. **Accuracy and repeatability:** Accuracy measurement is possible only when there is continuous output from the device and it is indicating type. However, flow switches can be the blind type also, so accuracy as defined and discussed in Section 1.2.1 of Chapter I may not be applicable for flow switches (or for that matter for any process switches). Flow switch may be indicating type or non indicating type. However, repeatability as defined in Section 1.2.1 of Chapter I, is applicable for flow switches.
2. **Actuation and deactuation point:** The actuation point refers to the set point. Actuation is that point exactly where the state of the electrical contact associated with the flow (process) switch changes state depending on the configuration of electrical contact(s), i.e., on reaching the set point, NC and NO contacts change states to become NO and NC, respectively. As long as flow is beyond the set point the change of state will not change. When the flow changes and returns to a point which is within the set point the electrical contact(s) will revert back to their original state. This point where the electrical contact(s) reverts back to the original state is referred to as the deactuation point. Theoretically both points should coincide but, in reality, these two points are never the same. The difference is called the differential or dead band. Refer to Fig. X/7.0.0-1B for detailed explanation.
3. **Adjustable set point:** As indicated above, the actuating point is referred to as the set point. When such a set point is adjustable it is referred to as an adjustable set point. Normally the set is adjustable within the measuring span of the instrument (refer to Subsection 1.2.1.7 of Chapter I). Normally the set point facility never exceeds measuring span.
4. **Dead band:** The dead band for process switches refers to the "differential" between actuation and deactuation in the flow (process) scale is called the dead band. Dead band is an important issue in connection with any process switch. There two types of dead band possible: fixed dead band and adjustable dead band. As the name signifies, when dead band can

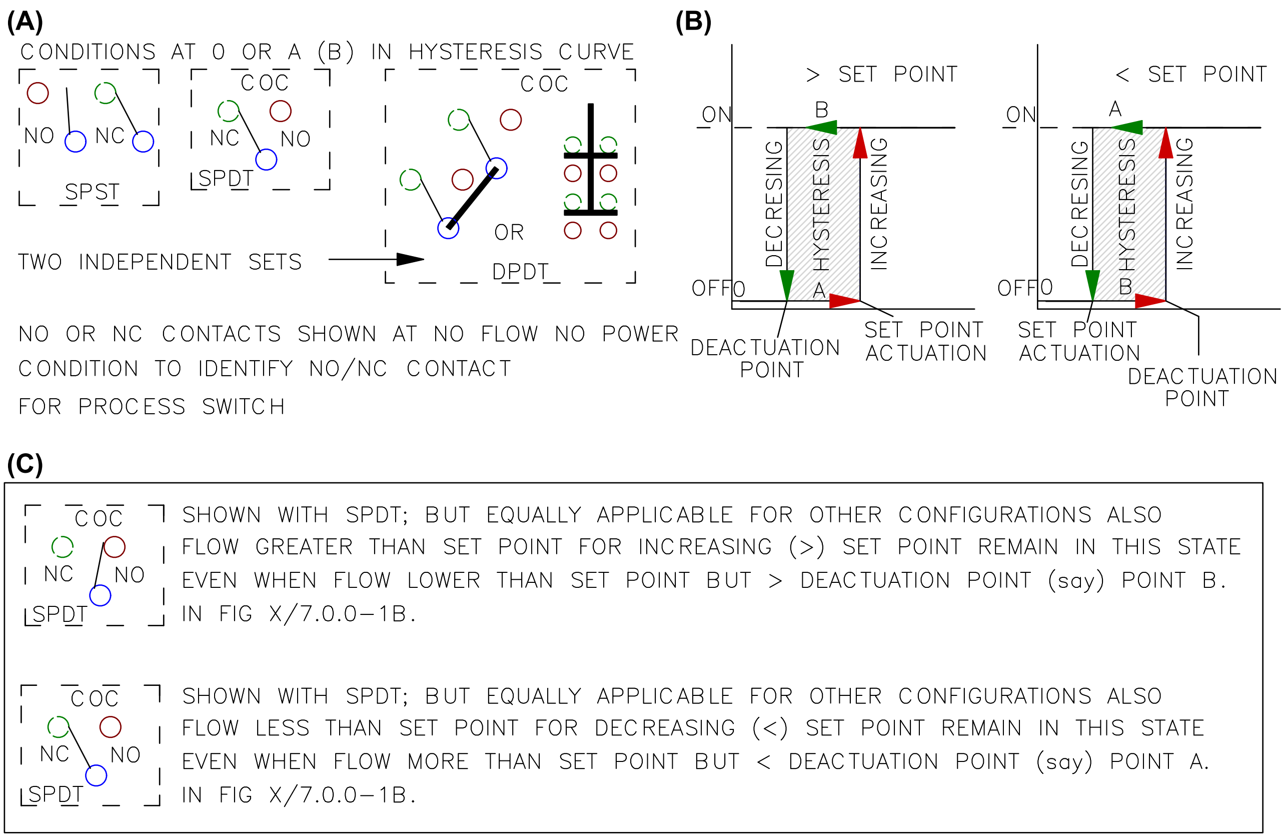

FIGURE X/7.0.0-1 Flow switch general terms explanations. (A) Contact configuration. (B) Hysteresis explained. (C) Contact actuation/deactuation conditions.

be adjusted (externally or by opening the switching unit) in a process switch it is adjustable dead band. When there is no adjustment facility in a switch it is fixed dead band. Dead band again can be two of types: narrow and wide dead band. Often dead band is used for, e.g., actuation of pump/fan, etc. Refer to Fig. X/7.0.0-1B

5. **Hysteresis:** Refer to Subsection 1.2.1.11 of Chapter I.
6. **Contact configuration:** As shown in Fig. X/7.0.0-1A, there are many contact configurations available, these are listed here:
   - *SPDT (COC):* Single-pole double-throw, i.e., single changeover element which at different conditions makes and breaks two separate terminals, i.e., one normally open, one normally closed, and one common terminal. This is also referred to as changeover contact (COC).
   - *DPDT:* DPDT stands for double-pole double-throw (DPDT). Same as SPDT only in this case there will be two independent changeover elements instead of one.
   - *SPST:* SPST is single-pole single-throw, i.e., when there is a single switch element and two terminals it is either NO/NC contact depending on initial configuration as elaborated in NO/NC contact decision discussed below.
7. **NO/NC contact decision:** Often we use the terms NO/NC contacts in connection with process switch. Therefore, how are NO or NC decided for a switch? Generally, the contact configuration is decided based on their condition at NO FLOW NO POWER CONDITION. Any switch when bought from market has no flow nor it is energized, so closed contact at this condition is NC and contact at open

condition is NO contact. The same philosophy applies for electrical switches and relays [9].

8. **Actuation or switching types:** Mercury actuated, microswitch, and magnetically actuated Reed switches are commonly used with flow switches. Of these, microswitches and snap-acting switches are mostly used because in many cases snap-acting switches meet or exceed industrial standards for reliability, electrical capacity, and longer life. Handling of a mercury switch is not easy and in many cases the help of hermetically sealed contacts may be needed for its operation. As seen above, mainly Reed switches and microswitches are deployed in flow and other process switches. We not us look at these issues in depth.
   - *Snap action (microswitch):* In microswitches the operation depends on working of a plunger and set of contacts between a common contact and, e.g., the NO/NC contact point. In a microswitch, when the plunger is completely released, i.e., in the *free position*, the common contact is against the normally closed contact to complete the circuit through them. In this condition, the normally closed circuit of the switch can carry current, and the common terminal is electrically insulated from the normally open terminal/contact. With depression of the plunger, the switch reaches the *operating point.* The distance from the free position to the operating point is called the *pretravel.* At the *operating point*, without further *movement of the plunger*, the common contact accelerates away from the normally closed contact [16]. Within a short time (a few milliseconds), the common contact strikes, bounces, and comes to rest against the normally open contact. This is snap action, and because of this action common contact cannot stop part way between the normally closed and normally open contacts. The distance the plunger travels past the operating point in the same direction is called *over travel.* Past *full over travel,* further depression of the plunger is prevented by the switch mechanism. The distance from the free position to the point of full over travel is called the *total travel.* When the plunger is released from the point of full over travel by further force, it goes past the operating point without any change in contact position till the plunger reaches the *release point*. Only at the release point, without further movement of the plunger, the common contact accelerates away from the normally open contact and within a few milliseconds the common contact strikes, bounces, and comes to rest, against the normally closed contact. The distance between the operating and release points is called the *differential travel.* The force and travel characteristics of the snap-action switch can be represented by graphical means, which is of interest to the designer.
   - *Reed switch:* Reed switches are available in a small glass bulb which is either a vacuum or filled with an inert gas like argon. The bulb is always sealed to prevent oxidation effect. Reed switches in process switch applications are operated with a magnet so that switches are made up of ferromagnetic material. However, nonferromagnetic material Reed switches are also available. Within the bulb, there is a flexible Reed strip contact. Operating force for the Reed switch, expressed in Ampere turns, is the minimum force necessary to close the Reed switch and this force is referred to as just-operate force. As the force between the poles increases as the gap decreases, a force of approximately half the just-operate force will maintain the operated state. Speed of operation of the Reed switch is determined by the excess of operating force over the just-operate force. Reed switch contact set has a comparatively lower breaking capacity of around 10–70 VA max. Therefore, this is suitable for low-power devices, such as DCS/PLC, solid state relay, etc. It is not suitable for circuits with more load requirements, such as motor circuits, solenoid valves, etc. For this reason, many flow

switches use Reed switches, along with built-in relay, e.g., SOR flap type flow switch.

- *Comparison between switch types:* The advantages and disadvantages between the two types of switches discussed above are been presented in Table X/7.0.1-1, so that the instrument designer can choose the best-suited type for the application in hand.

9. Manual reset: Set and reset of flow switches have been discussed above, however, there are some applications, where the manual reset feature is adapted to ensure that precautionary measures are taken before resting the switch manually. In such a way the operator is well aware of the situation, and necessary action is initiated.

7.0.2 FLOW SWITCH TYPES

There are two types of flow switches, one is the direct type and the other is the indirect type. Flow switches, such as the vane type and flap type, are direct flow switches. In contrast, flow switches with a flow element along with DP switches are an example of indirect flow switches. LVM in conjunction with a flow transmitter is another example of an indirect flow switch. Flow switches can be meant for fluids and others for solid flow. From a technology point of view flow switches can be divided into the following:

1. Paddle type;
2. In-line flow switch (piston);
3. DP type/bypass type;

TABLE X/7.0.1-1 Comparison Between Microswitch and Reed Switch

Important Issues	Snap Acting Switch	Reed Switch
Operating force	Larger force to operate	Lower force to operate
Volt, watt and capacity	Capable of handling larger voltages like 230/110 AVC and higher current-handling capacity	Much lower load-handling capacity and normally operates at lower voltages
Contact configuration	Possible wide range of contact configurations, like SPNO/NC, SPST, SPDT	This is not possible single contact
Time of operation	About 1 m/s, so time to make break is very nominal (1/1000) no radio frequency effect	Comparatively slower. May requires contact protection circuitry
Environmental effect	These are not hermetically sealed and necessary precaution/certification may be necessary for hazardous applications	Hermetically sealed in glass environment, free from contamination, safe to use in harsh industrial and explosive environments. Very high contact isolation resistance with very low contact resistance
Process switch application	Use with magnet is not applicable and needs force to operate	In-process switch applications can be used in combination with magnets and coils, to assist the operation. They can be used to form many different types of relays reed relay
Cost	Comparatively costlier	Much cheaper
Differential	Larger differential travels hence large process differential	Lower differential
Life expectancy	Good	Higher

4. Disc type switch (with push valve);
5. Reluctance type, such as capacitance/inductance type flow meters;
6. Thermal type (also hot wire anemometer);
7. Variable orifice area (vane/piston) type;
8. Ultrasonic (Doppler also);
9. Microwave type (solid flow switch);
10. Solid flow switch (US type).

We now us look into the details of flow switches starting with some general requirements.

7.1.0 General Requirements of Flow Switches With Explanations

Based on applicability and available flow switches the following are general requirements that can be specified. These are general requirements that may vary with a particular flow switch. However, these technical requirements should be specified for procurement. They are specified to facilitate the designer to draw up specifications.

1. **Sensing material:** Stainless steel or better for corrosion resistance. It is important to specify suitable material for the application.
2. **End connections:** Normally screwed of suitable size and style. However, in certain cases flange connections of suitable size, pressure rating, and standard are specified. Typical flanges are PN10, ANSI 150/300 lb class size depends on monitor size.
3. **Repeatability:** 5%−0.5% AR or better. There will be huge variations of repeatability of the flow switch depending on the technology and type of switch. In some cases mounting and improper installation can affect the value.
4. **Contacts:** Typical configuration: 2nos. SPDT snap acting dry contact. For usage in applications, potential free dry type contacts are preferred. Several combinations of contacts are specified with variations in ratings. The designer should choose the most suitable for the intended application.
5. **Contact rating:** To specify the maximum current at the maximum AC and DC voltages separately. Also, the maximum/minimum wattage should be specified. Normally manufacturers also specify these ratings, as while selecting it is important to note the minimum of the possible combination. This will be clarified from a rating, e.g., it may be specified 1 A at 110 VAC; 2 A at 30 VDC and power 30 W (VA). This means the maximum AC/DC voltage could be applied as 110 V and 30 V for AC and DC, respectively. However, the current should be limited so that 30 VA power is not exceeded. (e.g., for 110 VAC current < 0.27 A). The maximum currents that could be applied are 1 and 2 A but NOT at maximum voltage as it would be at lower voltage, e.g., 1 A AC is allowed with 30 VAC as wattage is limiting—hence voltage allowed to be selected accordingly.
6. **Set point:** Adjustable range to be specified.
7. **Dead band:** Application-dependent; to specify adjustable/fixed dead band. For fixed dead band narrow or wide range to be specified.
8. **Enclosure class:** Generally IP65.
9. **Minimum velocity and response time:** Another important issue is the minimum velocity of fluid that could be detected. Minimum velocity for detection varies widely with:
   - Type of fluid, i.e., gas (air) and liquid;
   - Type of sensing.

In gas this may vary between 0.1 and 70 m/s in liquid and gas. These variations given are based on various types of sensing element, i.e., thermal sensors have the capability to sense lower velocities, e.g., a thermal switch can sense 0.06 m/s velocity. On the other hand, the response time of the thermal sensor is not good enough as these have a higher time constant of around 6−8 s.

We now investigate the details of a few flow switches normally encountered in industrial applications. There could be a number of choices available, however only a few common types are covered here; specifications enumerated are generalized in nature—for specific details manufacturers need to be consulted.

7.2.0 Flow/No-Flow Switch: Paddle(/Vane) Type

Paddle/vane-operated flow switches are basically flow/no-flow switches mounted vertically in a pipe. Depending on the pipe size, the paddle length varies to give flow actuation.

7.2.1 DESCRIPTIVE DETAILS OF PADDLE TYPE FLOW/NO-FLOW SWITCHES

This flow switch utilizes the force of the liquid flow to propel the paddle (vane) for detection of flow and no flow conditions. The switch consists of a body, O ring, paddle pivot, central extension rod, magnet, spring, and hermetically sealed Reed switch. As shown in Fig. X/7.2.0-1, the paddle is connected to the switching unit through a pivot connection.

Flow and no-flow detection is as discussed here:

1. **No flow:** At static condition, i.e., at no flow, the spring is expanded, and pressing the magnet vertically downward, so that the hermetically sealed contact is in the NO condition.
2. **Flow condition:** When flow occurs, due to flow, the paddle is thrust and raised to about 20–30 degrees, i.e., with flow the paddle moves (swings) about the pivot, to move out of the liquid path creating very low pressure loss of around 3 psi irrespective of flow rate. On account of this paddle movement, the vane extension arm moves against the spring, to give upward motion to the magnet that actuates (deactuates) a hermetically sealed Reed switch, where open or closed contacts are required to signal flow or no-flow conditions [Note that magnetic movements have not been shown since the movement is very small].
3. **Design variations:**
   - *Length:* There are two kinds of paddle available: short paddles for pipe sizes up to <40 mm and long paddles for pipe sizes between >40 up to 100 mm. Cut-off paddle lengths for different pipe lengths are marked on the paddle/vane of the long paddles. The paddle needs to be trimmed during installation to permit switch actuation during desired flow.
   - *Switching mechanism:* In the discussions above, we have considered magnet and

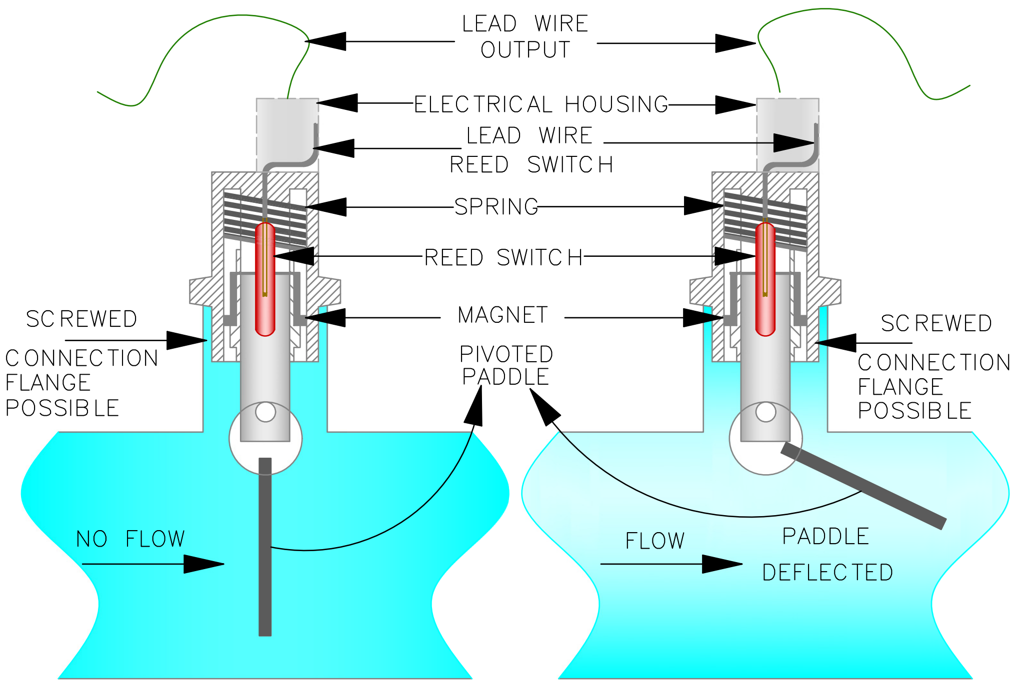

FIGURE X/7.2.0-1 Paddle type flow switch (flow/no flow).

Reed switches. There are variations in those also. Paddle type flow switches are also available with microswitches. In this type, in place of a magnet and Reed switch, microswitches are used. The paddle is pushed by liquid (water) flow, which actuates the microswitch. When the flow is decreased, it is deactuated. This simple microswitch is used for vertical mounting. There is another version where a flap is provided with a magnet for horizontal mounting for flow from top to bottom or bottom to top. This is a gravity pullback paddle switch, e.g., *R1Y(R1E) for PN10 DN63 of JPC France (www.jpcfrance.fr)*. When flow occurs, the paddle swings away, causing the Reed switch to operate, i.e., the contact closes. When flow decreases the paddle returns to its original position, and the Reed switch deactuates. To assist the swinging of the paddle the device is operated with a set of magnets and a repelling force of magnets (one in the paddle) assists swinging.

- *Mounting:* Normally paddle switches are meant for vertical mounting. A gravity pullback paddle switch is meant for horizontal mounting.

7.2.2 INSTALLATION REQUIREMENTS OF PADDLE TYPE FLOW SWITCHES

The following installation points need to be accounted for during installing of the switch:

1. **Orientation:** Vertical;
2. **Connection:** Screwed through 1″or 1½″ NPT/BSP connections;
3. **Flow direction:** To make sure that the marked flow direction is parallel to the pipe run;
4. **Pivot length:** Since the pivot length is directly related to the flow actuation and deactuation point so the paddle length (duly marked on the paddle for various pipe diameters) is to be trimmed at the site based on the pipe diameter;
5. **Straight length:** Minimum 3D (internal diameter of pipe) horizontal straight length to be kept on both sides of the flow switch;
6. **Operating conditions:** The operating pressure temperature specified by the manufacturer should not be exceeded. Such temperature does not have much effect, yet, with a change of temperature if there is a chance of changes in liquid density it may affect the thrust on the paddle like a pressure change affecting the thrust. In case of the possibility of sudden changes in operating conditions the manufacturer's recommendations are to be followed. Installation should be made at a place with the least possible shock and vibration.

7.2.3 SPECIFICATIONS OF PADDLE (VANE) TYPE FLOW SWITCHES

Based on reputed manufacturers' data, a brief generalized specification of a paddle (vane) type flow/no-flow switch is given in Table X/7.2.0-1. The table shows the maximum possible data, to the best of author's knowledge, and hence they may not be possible in any single switch. Based

TABLE X/7.2.0-1 Specification of Paddle (Vane) Type Flow/No Flow Switch

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Orientation	Vertical		
2	Connection Type	Screwed/flanges also possible		
3	Connection size and ratings (as applicable)	1″ NPT through 6″ Thread: 1—2″ NPT/BSP Flange: 2½″ to 6″ ANSI 150/300 lb class		

Continued

TABLE X/7.2.0-1 Specification of Paddle (Vane) Type Flow/No Flow Switch—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
4	Approx. pressure drop	207 millibar (3 psi)		
5	Pressure limit	<340 barg		
6	Temperature	−40 to 200°C		
7	Min. velocity	0.3 m/s (1 FPS)		
8	Pipe sizes	Short 1¼″ long In 1½″ to 4″ To trim the paddle accordingly		
9	Min./max. actuation *(deactuation)* flow in **L/min**	Short: 18 (*11.3*) to 109 (*83*) Long: 57 (*42*) to 147 (*94*)		
10	Flap/spring material	304 SS or 316 SS/316SS		
11	Body material	Brass/316SS		
12	Piston material	Aluminum		
13	Other parts	Teflon/ceramic		
14	Electrical housing	IP65 with explosion certification from appropriate authority as necessary		
15	Output	Contact output with relay		
16	Contact configuration	SPST/SPDT with relay or low-power SPST and SPDT		
17	Contact rating	Refer to Subsection 7.1.0.5 for explanation. Available in AC: V(max) 110 V I max: 0.9 A DC: 30 V I 2 A Max Watt: 30 VA		
18	Repeatability	5% AR average		
19	Hazardous application	Necessary certificate from authorized agencies		

on the application, the required data may be modified after consulting the manufacturer.

7.3.0 In-Line and DP Type Flow Switches

In this section two types of flow switches are discussed and both use a piston, magnet, and Reed switch for their operation. These two types are the in-line (piston) flow switch and the DP type flow switch. The discussions start with the in-line flow switch.

7.3.1 IN-LINE (PISTON) FLOW SWITCH

A typical in-line piston flow switch is depicted in Fig. X/7.3.0-1.

1. **Principle of operation:** An in-line flow switch consists of a moving piston, a magnet in the piston, and a hermetically sealed Reed switch unit, as shown in Fig. X/7.3.0-1. Major parts of the flow switch have been marked in this figure. The Reed switch is magnetically

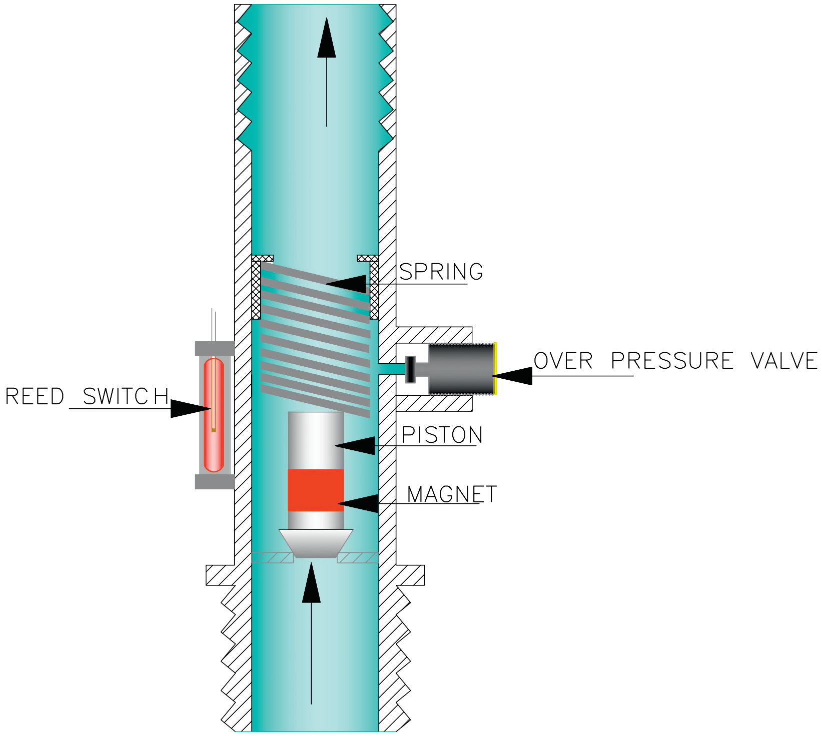

FIGURE X/7.3.0-1 In-line (piston) flow switch.

coupled with the piston and magnet. In this type of construction, as shown, the wetted area is completely separated from the electrical area, hence there is no sealing problem. These are basically meant to be used in vertical mounting. With flow of liquid from bottom to top, due to flow/increase in flow of fluid, the piston is displaced by the differential pressure from fluid flow. The piston has a magnet which, due to displacement of the piston, also moves up. On account of the movement of the magnet, the Reed switch is actuated. On the other hand, when the flow stops or decreases, due its own weight the piston and magnet comes down and the Reed switch is naturally deactuated. Then what is the purpose of the spring? Return of the piston is carried out by the spring. When the flow of fluid is from the top to bottom, then the spring is more necessary to retract the piston. Also, it helps in regulating the movement of the piston. In this design the piston is placed directly in the 100% flow path. There is another version also which uses a flap with a magnet. The flap with a magnet is also placed directly in the 100% flow path. In-line flow switches are often provided with overpressure protection, as shown in Fig. X/7.3.0-1. In the case of a piston there is linear movement of the piston, in the case of a flap, it swings around a pivot in the main body. The operation is similar to those discussed in Section 7.2.0 above. The action and construction are the same. These meters are available in various sizes and normally have screw type end connections.

2. **Specification:** Specification of an in-line flow switch has been enumerated in Table X/7.3.1-1

TABLE X/7.3.1-1 Short Specification of In-Line (Piston) Flow Switch

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Liquid (mainly water)		
2	Orientation	Vertical		
3	Connection type	Screwed		
4	Connection size	½″ BSP/NPT (M) at inlet and female at outlet		
5	Pressure limit	1 MPa (PN10)		
6	Temperature	0−100°C		
7	Ambient temperature	0−50°C		
8	Pipe sizes	Small up to 15 mm		
9	Set adjustability	Adjustable through piston		
10	Body/piston material	Polyphenylene oxide (PPO)/stainless steel		
11	Spring material	304 SS		
12	Electrical housing	IP65		
13	Output	Potential free dry contact		
14	Contact configuration	NO		
15	Contact rating	Refer to Subsection 7.1.0.5 for explanation. Available in: AC: V(max) 230 V Current: 1 A Max Watt: 70 W.		
16	Repeatability	2%−3% AR Average		
17	Hazardous application	Necessary certificate from authorized agencies		

7.3.2 DP TYPE FLOW SWITCH

From the discussion on the DP type flow meter and DP type flow metering it has been seen that flow through the flow element is proportional to the square root of DP across a flow element. DP type flow switches basically work on the principle of measurement of DP across a flow element and generating a contact at the desired DP and hence flow point.

Description: DP flow switches operate on the differential pressure principle without any bearing or sliding surfaces to corrode and stick. DP type flow switches can be used for both gas and liquids, as well as for dirty fluids. Fig. X/7.3.0-2 shows a typical DP type flow switch. This basically is a flow element with a DP gage with suitable contact. These flow switches can be blind type also. Use of both a snap-acting switch with a DP gage is quite common. Some also use a Reed switch and magnet placed either on the lever mechanism of the indicator or to sensor such sensing bellow so that when the desired DP is reached the Reed switch closes contact. Some use a Reed relay in place of a Reed contact to facilitate the switching action, as already discussed above. Normally there are different versions for liquid and gas applications. Many of these flow switches have an indication for flow also and it is possible to adjust the flow set points. There can be one or two field-adjustable

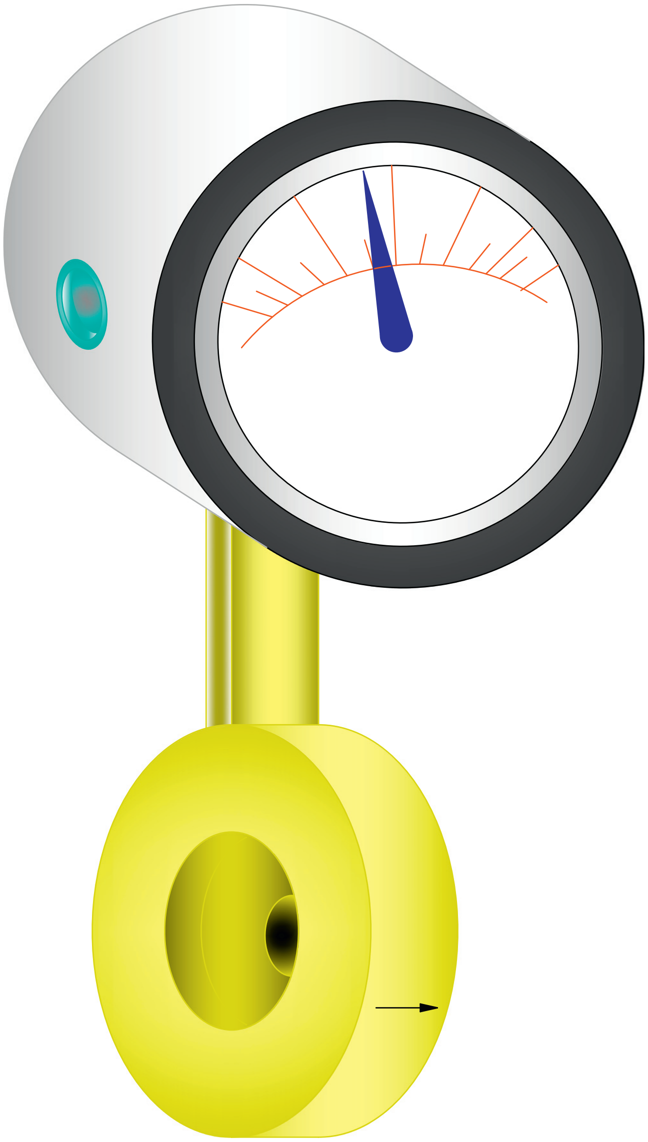

FIGURE X/7.3.0-2 DP type flow switch.

switch set points. Some of these flow switches have a built-in terminal box. Most of these flow switches are suitable for hazardous applications. These are reliable but may not offer good repeatability and accuracy (applicable for flow switches with indication).

Specification: Table X/7.3.2-1 presents brief specification of the flow switch type.

7.4.0 Variable Orifice Type Flow Switches

A typical variable orifice type flow monitor is shown in Fig. X/7.4.0-1. There are two types of such variable orifice type flow monitors: vane type and piston (valve) type.

Operating the vane against the spring is the major component of the flow switch. Functioning of the system has been explained in two sets of figures shown on the right hand side of Fig. X/7.4.0-1. As shown in the figure, this is a flow monitor with flow indication and flow switch, e.g., FLW series of flow monitors from Omega Engineering USA.

7.4.1 WORKING PRINCIPLE OF VARIABLE ORIFICE FLOW SWITCH

The kinetic energy of a flowing liquid/gas is utilized to move a spring-biased swing vane. On account of flow, a vane is swung against a spring in a vane type instrument or piston/disc (valve) seat against the spring in a piston (valve) type flow monitor. When the vane (left side figure in Fig. X/7.4.0-1)/seat moves there will be variations in the

TABLE X/7.3.2-1 Brief Specification of DP Type Flow Switch

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Liquid and gases/air		
2	Orientation	Horizontal		
3	Connection type	Screwed/flange		
4	Connection size	BSP/NPT (M) based on meter size. Flanges 150/300 lb ANSI flange (wafer type as shown available)		
5	Pressure limit	30 barg		
6	Pressure drop	Depends on element around 0.7 Kg/cm^2.*		*Ref: manufacturer

Continued

TABLE X/7.3.2-1 Brief Specification of DP Type Flow Switch—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
7	Temperature	−30 to 180°C		
8	Ambient temperature	0–50°C		
9	Pipe sizes	15–200 mm		
10	Flow range	Liquid: 8–12 KL/min Gas: 15–2000 Nm^3/h		
11	Set adjustability	Adjustable max. two set points settable		
12	Body	Bronze, stainless steel, also Monel possible		
13	Housing	Aluminum/SS		
14	Sensor materials	Bronze, stainless steel, Ionel/Inconel		
15	Electrical housing	IP65/IP66		
16	Output	Potential free dry contact		
17	Contact configuration	One or two SPDT		
18	Contact rating	Refer to Subsection 7.1.0.5 for explanation. Available in: AC/DC: V(max) 230 V Current: 1 A Max Watt: 10 W		
19	Repeatability	1% AR average		
20	Hazardous application	Necessary certificate from authorized agencies		

Data given here are based on reputed manufacturer and maximum possible conditions have been considered so, may not match any particular model.

flow passage, i.e., variation in orifice size proportion to the flow rate of the fluid. The vane is mechanically linked to a pointer to indicate the flow rate on a scale. This linkage to the indicator pointer is also used to actuate the switching unit as shown in Fig. X/7.4.0-1. During no-flow condition, the vane closes the flow path due to spring action. There could be another piston (valve) type design shown in the RHS of Fig. X/7.4.0-1, here the piston rests on the seat. When flow starts, the kinetic energy of the fluid overcomes the spring force to admit and establish fluid flow. In the case of a vane type design, the vane is forced to swing, creating an opening for fluid flow. Similarly, in the piston (valve) type design shown in on the RHS of Fig. X/7.4.0-1, trim is forced against the spring, allowing flow to take place. In instruments, switches are available with magnetic coupling, e.g., the disc type flow switch of Magnetrol. In both cases, on account of the design, the flow admitted is proportional to the orifice opening. The movement of vane or piston arrangement is linked with a flow indicator and switching unit. When flow increases the linkage compresses the switching unit, so that when flow exceeds the desired set point the switch actuates. Similarly, when the flow decreases, the switch is deactuated. For vertical upward flow, a Rotameter with contact can be used for flow switching also. This is also a variable orifice flow switch used in industrial applications.

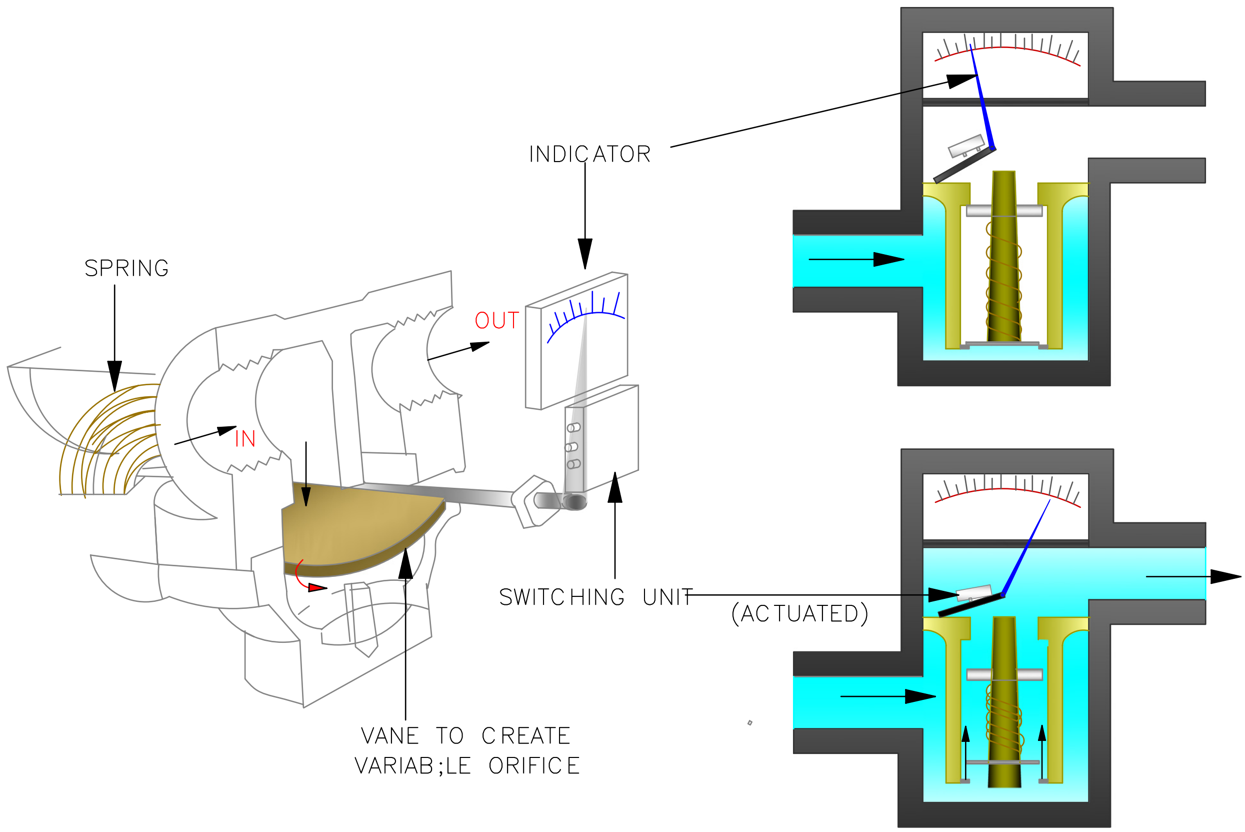

FIGURE X/7.4.0-1 Vane type flow switch.

7.4.2 SPECIFICATION OF VARIABLE ORIFICE FLOW SWITCHES

The specification of a variable orifice flow monitor has been enumerated in Table X/7.4.2-1.

7.5.0 Thermal Dispersion Type Flow Switch (Monitor)

Solid-state designs of thermal dispersion flow switches are quite popular in industries. This is a

TABLE X/7.4.2-1 Specification of Variable Orifice Flow Switch

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Liquid and gases/air		
2	Orientation	Horizontal/vertical		
3	Connection Type	Screwed/flange		
4	Connection size	BSP/NPT (M) based on meter size. Flanges 150/300 lb ANSI flange		
5	Pressure limit	Around 25 barg		
6	Pressure drop	Type dependent around 0.2 barg*		*Refer to manufacturer
7	Temperature	−18 to around 100°C		

Continued

TABLE X/7.4.2-1 Specification of Variable Orifice Flow Switch—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
8	Ambient temperature	0–50°C		
9	Pipe sizes	15–100 mm		
10	Flow range	3–350 Lpm		
11	Set adjustability	Adjustable set point settable		
12	Wetted parts	Stainless steel		
13	Seal	PTFE		
14	Electrical Housing	IP65		
15	Output	Potential free dry contact		
16	Contact configuration	One or two SPDT		
17	Contact rating	Refer to Subsection 7.1.0.5 for explanation. Available in: AC/(DC): V(max) 110/230 V Current (max): 10 A Max watt: 120 W		
18	Accuracy	3% FSD for indication		
19	Repeatability	1% AR Average		
20	Hazardous application	Necessary certificate from authorized agencies		

mass flow detection type monitor and is available in different designs. Since they measure mass they are immune to changes in viscosity and density. These can be used in slurry and fluid with particle applications. It is very sensitive and capable of measuring small changes in flow.

7.5.1 THEORETICAL BACKGROUND OF THERMAL DISPERSION FLOW MONITORS

Thermal dispersion type flow switches sense the stoppage or movement of the process stream, i.e., the mass flow of fluid by detecting the temperature change, i.e., the cooling effect of the sensing probes as detailed, with the theoretical background of thermal dispersion type flow metering, in Section 4.0.2 of Chapter VI. These are available as a probe or a flow through device (with transmitter). So, basically the system should consists of one heating element, one reference sensor, and another sensing probe, as shown in leftmost figure of Fig. X/7.5.0-1. As has been noted in Chapter VI, this is a mass flow detection, hence it is independent of density and is able to detect very small changes. On the other hand, as this is thermal sensing, like any other thermal/temperature sensing the method has a higher time constant, therefore instantaneous changes may not be detected properly. Based on the fluid type, i.e., heat transfer capability and device adjustment, the response can be in seconds or minutes [15].

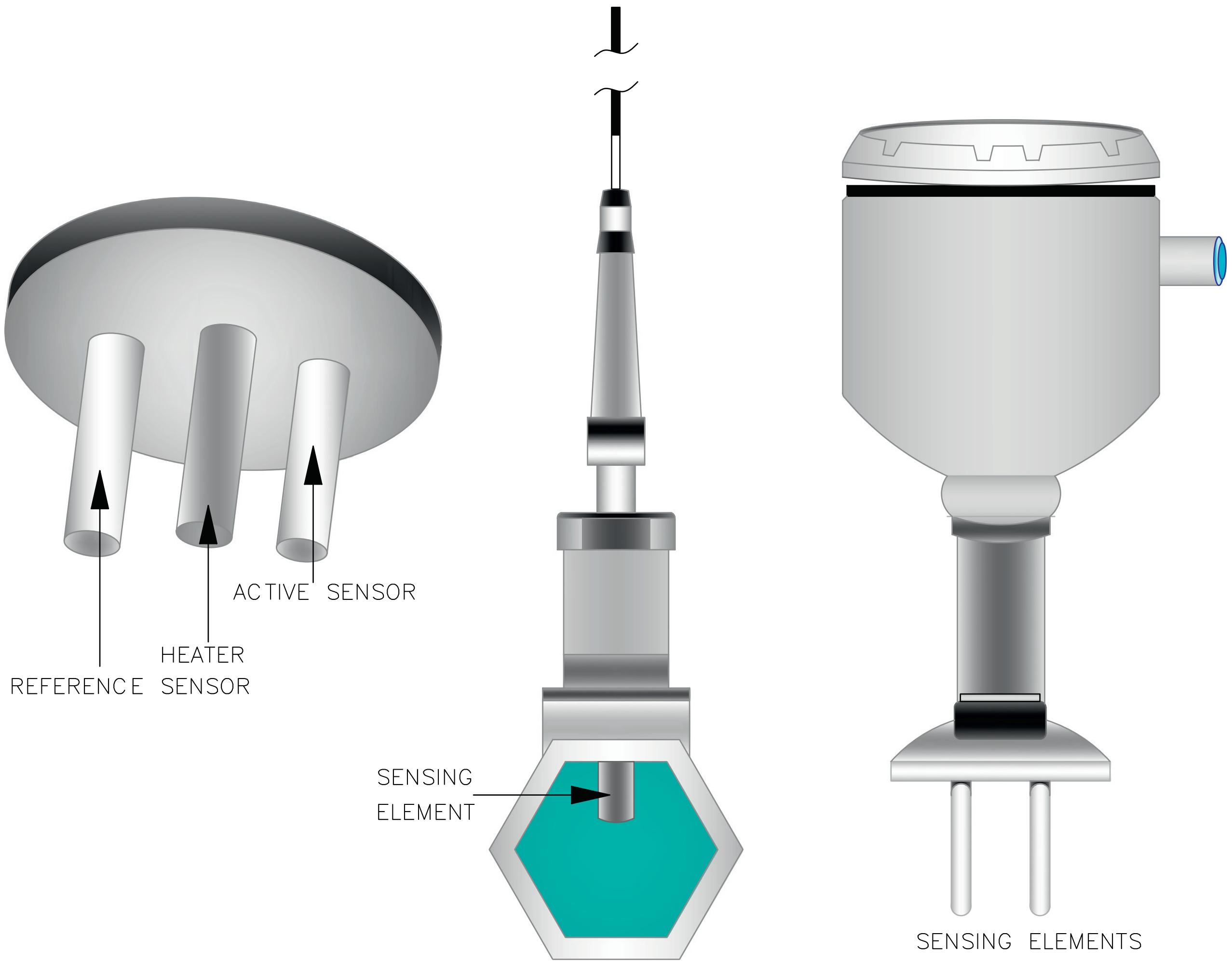

FIGURE X/7.5.0-1 Thermal type flow switch (monitor).

7.5.2 DESCRIPTION OF THERMAL TYPE FLOW SWITCHES

As stated above, a thermal flow switch/monitor utilizes thermal dispersion principles, i.e., cooling effect of flowing fluid is used to measure the mass flow rate of fluid (liquid/gas). The sensor consists of two RTD (or transistors) sensors and a heating element. One sensor is located at the sensor tip very close to the flowing medium, while the other one is a reference sensor meant to sense the ambient condition of the fluid. In order to create the temperature difference one of the sensors is heated through a heater by applying power. The differential is greatest when no liquid (dry condition) is present when there is fluid (i.e., liquid) on account of flow and quenching action, the temperature differential would decrease. When flow is in the conduit, the heated sensor will be cooled more. The cooling effect is a function of how fast heat is conducted through the flowing fluid. Therefore, there will be a difference of temperature between the two sensors. When the velocity of fluid flow is slow, then the temperature difference would be greater, while for faster velocity the difference will be less. This is because temperature sensing has a higher time constant. From this it is clear that the differential temperature between the two sensors is a function of the fluid velocity and hence flow. Normally these types of instruments are available in the form of monitoring instruments, i.e., for continuous measurement and switching is just a part of it. Some of

these instruments are provided with built-in LED indicators to indicate normal and abnormal conditions. Many of these instruments are often used for two fluid (hydrocarbon and water) interface detection, and level detection also, e.g., the T21 thermal differential instrument of SOR or the TS thermal dispersion switch. In continuous casting machines these types of flow switches are often used, usually for granular solids.

7.5.3 SPECIFICATION OF THERMAL FLOW SWITCHES

The specification of a thermal flow switch/monitor has been enumerated in Table X/7.5.3-1. The values/data provided here are from reputed manufacturers. The maximum possible data have been indicated as far as possible; naturally all may not be available with a single device.

7.6.0 Discussions on Miscellaneous Flow Switches

There are a few other types of flow switches, such as ultrasonic flow monitoring based on transit time and Doppler type, as already covered in Chapter V. There are a few other types also, these are capacitance type flow/no-flow switches and bypass type switches.

1. **Ultrasonic flow monitor:** Both transit type and Doppler effect flow monitors are used to monitor flow. This is very useful in retrofitting applications as these types of flow monitors can be mounted external to the pipe and no shutdown is needed. Basically these are flow meters with variations as described in Section 6.0.0 of Chapter V. In view of this these are not repeated again here. For switching action necessary contact outputs are generated at

TABLE X/7.5.3-1 Specification of Thermal Flow Monitor

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Fluid type	Liquid and gases/air		
2	Mounting and insertion length	Mounted from the top, in the conduit with variable insertion lengths		
3	Sensor length	From 40 up to 3000 mm		
4	Connection type	Screwed male or female (Tee type fitting) or with tri-clamp sanitary fitting		
5	Connection size	½″, ¾″ to 2′ NPT/G/BSP threads		
6	Pressure limit	Vacuum to 300 barg		
7	Temperature range	−70 to 200°C		
8	Ambient condition	−40 to 60°C with high humidity (>95%)		
9	Pipe sizes	15−500 mm		
10	Flow range	3−100 Lpm		
11	Set adjustability	Liquid: 3 mm/s to 2 m/s Gas: 0.1−150 m/s		
12	Body and wetted parts	Stainless steel 316		
13	Housing	Aluminum powder coated		
14	Electrical housing	IP65/66		
15	Output	Potential free dry contact		

Continued

TABLE X/7.5.3-1 Specification of Thermal Flow Monitor—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
16	Contact configuration	One or two DPDTs with relay		
17	Contact rating	Refer to Subsection 7.1.0.5 for explanation. Available in: Direct: 30 VAC at 50 mA and 42 VDC at 65 mA. With relay: 8 A at 250 VDC		
18	Accuracy	3% FSD for indication; set point about 10%		
19	Repeatability	1% AR Average		
20	Differential adjustment	15%–20%		
21	Power supply	24 VDC/AC or 240 VAC		
22	Hazardous application	Necessary certificate from authorized agencies are possible		

the desired set point from the secondary electronics.

2. **Capacitance type flow switch:** These are mainly used for liquid flow sensing. These are flow/no-flow sensing switches. This capacitance switch type is fitted between two flanges in standard pipe sizes between 50 and 200 mm [15]. It is known that air has a dielectric constant of 1, therefore when there is liquid flow, the dielectric constant of the flowing fluid will be greater than 1. Therefore, when there is no flow (empty), the dielectric will be low radio frequency (RF) current. When flow of liquid is established, the dielectric will be higher, giving rise to higher RF current. In secondary electronics the higher current will be detected to generate contact output. These contacts can be used for protection of the pump. An adjustable time delay of 0–20 s is provided to protect from premature shutdowns [15].
3. **Bypass type flow switch:** There is another kind of flow switching popularly known as the bypass type flow switch. In the main line there will be a differential pressure-producing vane. On account of flow in the main line a proportionate part of the flow will be diverted to the bypass line where there will be a magnet. On account of flow in the bypass line the magnet will be deflected and the position of the magnet and Reed switch can be externally adjusted. Therefore, based on the deflection of the magnet the Reed switch will be operated.

With this, the discussions on fluid flow switches come to an end and we now investigate flow switches for solid and bulk materials.

7.7.0 Discussions on Solid (Bulk) Flow Monitors

In solids handling systems, it is necessary to quickly detect any abnormal conditions such as blockage/feed loss, leakage of bag filter, etc. These are extremely important for cement plant fly

ash handling in power plants and alumina plants, etc. Flow monitor utilizing microwave and electric charges is often used for not only detection of flow/no-flow conditions but also for continuous flow monitoring. Electric charge type devices, such as the "Triboflow," collect, on their probe surface, the static charges of the solid particles passing over their surface. The resulting current is related to the flow rate of solids [15]. Microwave type flow measurement for solid flow has been discussed in detail in Section 5.0.0 of Chapter VIII. The discussion starts with microwave type solid flow monitors.

7.7.1 MICROWAVE TYPE SOLID FLOW MONITORS

By now, the reader will be well aware of the microwave type flow monitor discussed in Section 5.0.0 of Chapter VIII. However, discussions now start with a short recap of the measuring principles.

1. **Principle of operation discussions:** Microwave-type solid flow measurement is used mainly for granular solid materials and dusts. Microwave-type solid flow measurement utilizes the Doppler effect for monitoring of solid flow. These instruments consist of a transmitter and receiver. The transmitter emits a microwave signal around 24 GHz towards the flowing solids. The signal is reflected by the flowing solid particles. This reflected signal is received by the receiver. On analyzing the reflected frequency (Doppler effect), the velocity of the flowing solid particles is determined. On account of the material motion there will be a change in the frequency of the reflected signal. Thus when the material is in motion, the returned signal will have a frequency different from the emitted signal. On the other hand, when there is no motion, the returned signal will be the same frequency as the emitted signal. Normally a microwave type instrument is not affected by material build up. As stated earlier, since these are flow monitors (i.e., capable of continuous measurement) they offer adjustable set points. It is possible to detect a wide range of flow velocities of solids. A typical flow monitor with application details is depicted in Fig. X/7.7.1-1.
2. **Penetration:** With very little attenuation microwaves can penetrate nonconductive materials, e.g., plastic, glass, and wood. Nonconducting material build up on the wall has hardly any effect. Table X/7.7.1-1 gives the wall thickness values for various materials [17].
3. **Functional application area:** As shown in Fig. X/7.7.1-1, some of the functional application areas include but are not limited to:
   - Mechanical conveyor;
   - Silo discharge;
   - Feeders;
   - Dryers;
   - Mixing unit;
   - Grinding.
4. **Industry application areas:** Industry-wise application includes but is not limited to the following:
   - Cement;
   - Gypsum;
   - Woodchip;
   - Fertilizer;
   - Powder;
   - Food items/products;
   - Animal feed;
   - Coffee and granular materials.
5. **Features:** The features of microwave solid flow switches include but are not limited to the following:
   - Highly reliable solid mass flow measurement;
   - Noninvasive measurement;
   - External mounting hence easy for retrofitting;

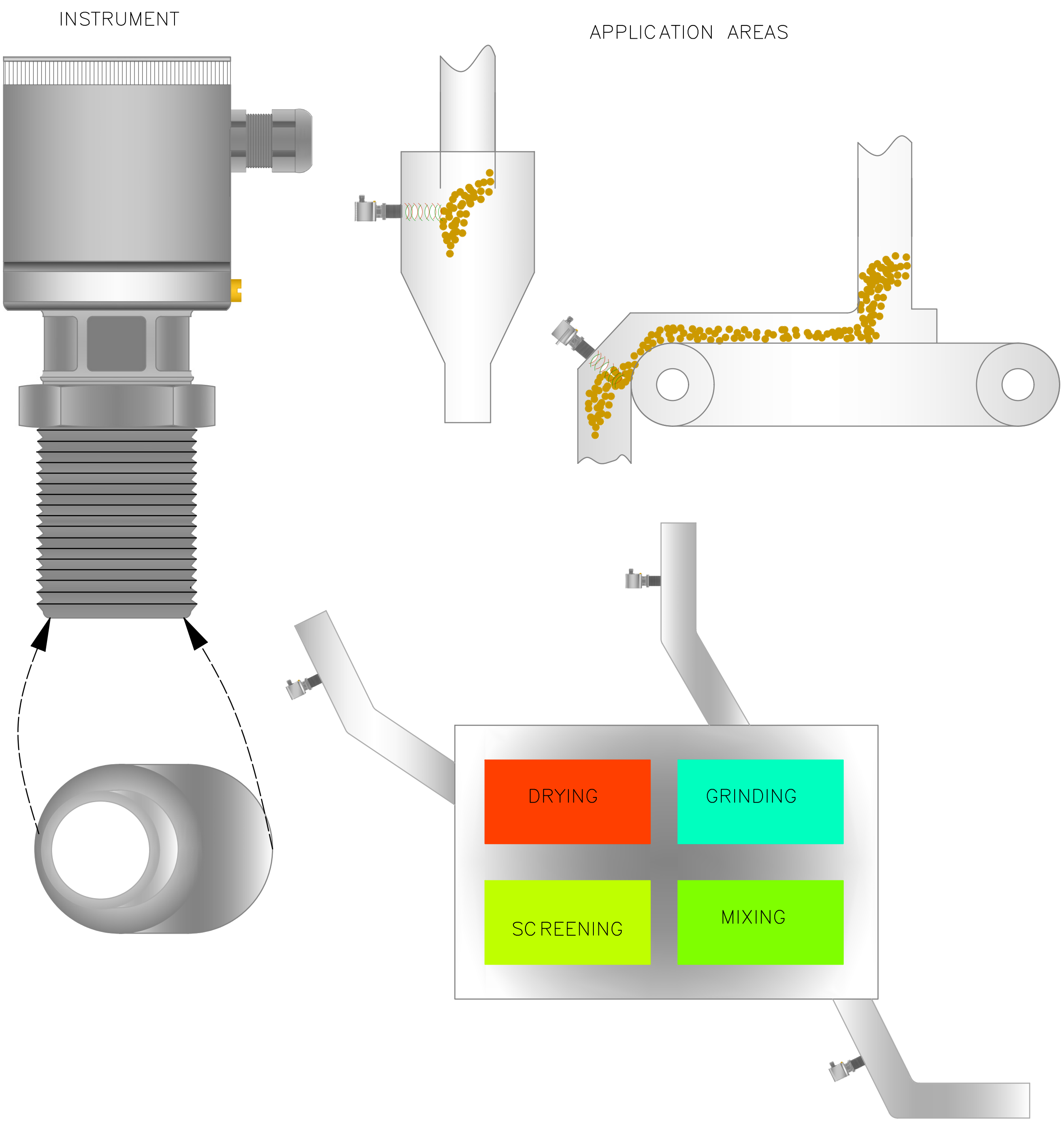

FIGURE X/7.7.1-1 Microwave solid flow switch. *Developed based on Measuring Systems for Solids, Mutec instruments (Catalog). http://www.muetec-instruments.de/wp-content/uploads/2016/04/LC510M-brochure.pdf. Courtesy: Mutec instruments; Developed based on Thermo Scientific Granuflow GTR 130 Flow/No-Flow Detector; Technical catalog—product Specification, Thermoscientific; Thermo Fisher. https://assets.thermofisher.com/TFS-Assets/CAD/Specification-Sheets/D10578~.pdf. Courtesy: Thermo Fisher.*

TABLE X/7.7.1-1 Microwave Signal Penetration

Wall Materials	Wall Thickness (mm)
Glass	25–50
Wood (dry chip board)	13–25
Plastic (PVC PE PTFE)	<100

Thermo Scientific Granuflow GTR 130 Flow/No-Flow Detector; Technical catalog—product Specification, Thermo-scientific; Thermo Fisher. https://assets.thermofisher.com/TFS-Assets/CAD/Specification-Sheets/D10578~.pdf. Courtesy: Thermofisher.

- Suitable for all bulk material granular material;
- Adjustable sensitivity, damping, hysteresis, and filter time [18];
- Very easy installation.

6. **Specification:** A brief specification of a microwave solid flow monitor has been enumerated in Table X/7.1.1-2. The technical data enlisted here are from reputed manufacturer and the best possible data have been presented, so naturally these may not be available in single instruments.

TABLE X/7.1.1-2 Specification of Microwave Solid Flow Monitor

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Material type	Bulk solid/granular material		
2	Mounting	Mounted externally in any orientation as shown		
3	Connection type and size	Screwed 1″ or 1 ½″		
4	Sensor surface	Teflon		
5	Pressure limit	25 barg		
6	Temperature range	−20 to 80°C		
7	Ambient condition	−20 to 60°C		
8	Operating frequency	~24 GHz		
9	Set and dead band	Yes Adjustable		
10	Body and wetted parts	Stainless steel 316		
11	Electrical Housing	IP65/66		
12	Power supply	30 VDC/AC		
13	Detection range	0–1.8 m		
14	Output	Potential free dry contact		
15	Contact configuration	One or two SPDT with relay		
16	Contact rating	Refer to Subsection 7.1.0.5 for explanation. Available in: 250 Vmax, 4 Amax 500 VA (Max)		
17	Damping	0–10 s		
18	Repeatability	1% AR average		
19	Indication	LED		
20	Hazardous application	Necessary certificates from authorized agencies are possible		

7.7.2 ELECTRIC CHARGE TYPE FLOW MONITORS

An electric charge-based flow switch is known as a "Triboflow." When solid particles pass over the probe surface static electric charges are collected on the surface of the probe. These charges give rise to current, which is related to the flow rate of solids. These probes are sensitive to small changes in solid flow. A typical electrical charge flow monitor is shown in Fig. X/7.7.2-1.

This type of flow monitor can be used for continuous bulk solid flow metering, as well as as a flow switch. This is a ring sensor, the measurements are taken integrally and without contact over the pipe cross-section [18]. As stated earlier, on account of the flow of solid particles, charges are developed and these electrically charged particles produce a charge signal against the grounded conveyor duct. On the basis of statistical fluctuations in the particle flow, a current noise is produced which depends on the solids concentration and also on the solids velocity [18]. Stationary particles, such as sediments, do not contribute to the results. A brief specification has been enumerated in Table X/7.7.2-1.

On account of a few limitations of this kind of measurement and nonapplicability for all kinds of materials as well as installation issues, continuous

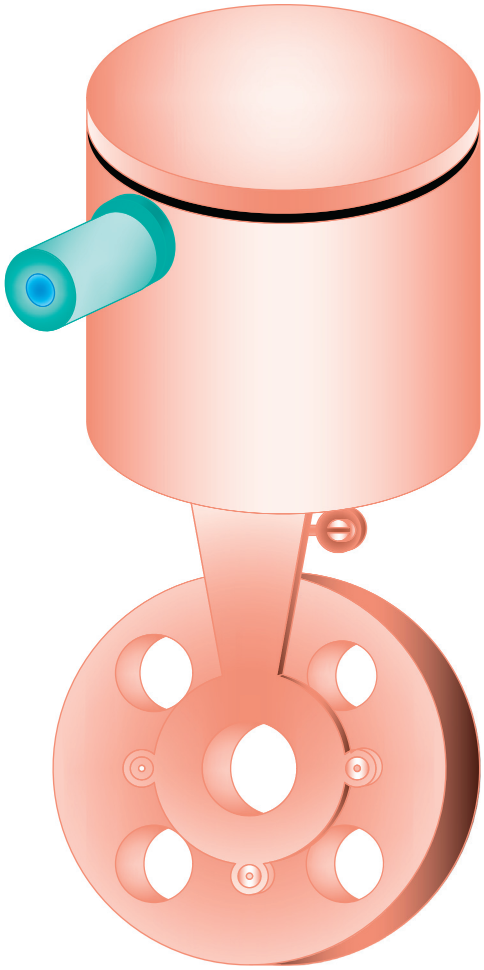

FIGURE X/7.7.2-1 Electric charge type flow switch.

TABLE X/7.7.2-1 Specification for Electric Charge Type Solid Flow Monitor

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Material type	Bulk solid/granular material		
2	Mounting	Between flanges or in flanged pipe		
3	Connection type and size	Flange DIN/ANSI or screwed version also available		
4	Sensor surface	Teflon		
5	Pressure limit	40 barg		
6	Temperature range	−20 to 90°C		
7	Ambient condition	−20 to 70°C		

Continued

TABLE X/7.7.2-1 Specification for Electric Charge Type Solid Flow Monitor—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
8	Set and dead band	Yes adjustable		
9	Body and wetted parts	Stainless steel 316		
10	Electrical housing	IP65/66		
11	Power supply	17–30 VDC		
12	Build up effect	Generally no effect		
13	Damping	0–10 s		
14	Output	Potential free dry contact continuous measurement possible		
15	Contact configuration	One or two SPDTs with relay		
16	Contact rating	Refer to Subsection 7.1.0.5 for explanation. Available in: 50 Vmax, 1 Amax 500 VA (Max)		
17	Current consumption	Nominal		
18	Repeatability	1% AR average		
19	Indication	LED		
20	Hazardous application	Necessary certificates from authorized agencies are possible		

measurement of solid flow with this type of flow metering is not very popular in solid flow measurement.

Flow conditioning computation and controls are important aspects of flow measurement. We now conclude the discussions on special instrumentation chapter with a special call out below (Fig. X/7.7.2-2). In the next chapter let us investigate other important aspects on flow measurement to cover the discussions on flow conditioning, computation and controls in next chapter.

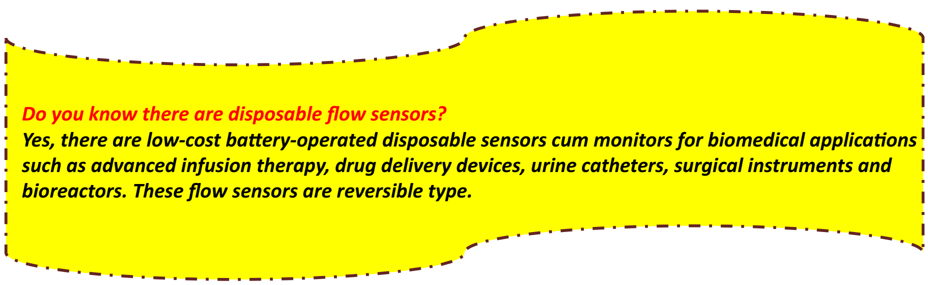

FIGURE X/7.7.2-2 Disposable flow sensor.

LIST OF ABBREVIATIONS

ABS Absolute
AC Alternating current
ADC Analog to digital converter
AI Analog input
AO Analog output
AR Actual reading (in connection with accuracy)
CCW(/CW) Counterclockwise (/clockwise)
CMRR Common mode rejection ratio
CMV Common mode voltage
COC Change over contact
CS Carbon steel
DAS Data acquisition system
DC Direct current
DCS Digital control system
DI Ductile iron/digital input
DO Digital output
DP Differential pressure
DPDT Double-pole double-throw
DPT Differential pressure transmitter/transducer
DSP Digital signal processing
EMC Electromagnetic compatibility
EMI Electromagnetic interference
FAT Factory acceptance test
FC Fail to close (for valve)
FO Fail to open (for valve)
FSD Full-scale division (in connection with accuracy)
HVAC Heating ventilation and air conditioning
IC Integrated chip/internal combustion (engine)
ID Internal diameter
I/O Input/output
IS Intrinsic safety
LCD Liquid crystal display
LDA Laser Doppler anemometry
LDV Laser Doppler velocimetry
LED Light-emitting diode
LHS Left-hand side
LVM Limit value monitor
MS Mild steel (main steam)
MUX Multiplexer
MVT Multivariable transmitter
NB Nominal bore
NIST National Institute of Standards and Technology
OD Outer diameter
PLC Programmable logic controller
PTFE Polytetrafluoroethylene
PU Processing unit
PVC Polyvinyl chloride
PVT Pressure volume temperature
RF Raised face/radio frequency
RHS Right-hand side
RPM Revolutions per minute
RTD Resistance temperature detector
SIL Safety integrity level
SPDT Single-pole double-throw
SPST Single-pole single-throw
SS Stainless steel
STP Standard temperature and pressure (Fig. I/1.1.2-3)
T/C Thermocouple
US Ultrasonic/United States
VDU Visual display unit
VFD Variable-frequency drive
VM Valve manifold
W/O Without/water in oil (emulsion)
WRT With respect to

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CHAPTER XI

FLOW CONDITIONING COMPUTATION AND CONTROL

Chapter Outline

PREAMBLE

Basic flow meters and monitors of different types have been discussed at length in previous chapters. In some cases, like DP type flow, open channel flow measurements, for remote measurements differential pressure transmitters (DPTs), multivariable transmitters (MVTs), or level transmitters are necessary. To get an accurate flow measurement result it is necessary that the signal pickups and/or outputs have proper signal conditioning, (especially when DPTs, MVTs, etc. are not used). For flow computation, e.g., density corrections, flow computers (especially for compressible fluids) are essential. Also, to get the totalized flow value, a totalizer with an integrator is necessary. There are a number of ways for flow measurement presentation, i.e., various display types. Although in a programmable logic controller (PLC)/digital control system (DCS) many of these signal conditioning and computations can now be performed in them. However, with the introduction of built-in embedded systems and microcontrollers with the instruments, most of these functions are performed at field level in smart instruments. These are also preferred to facilitate fieldbus communication and system integration. BTU measurements are quite important for finding the efficiency of various heat exchanger units, which are present from building complexes, such as HVAC, to industrial applications, like boilers. Similarly, it is important to

Plant Flow Measurement and Control Handbook. https://doi.org/10.1016/B978-0-12-812437-6.00011-1

know the fuel and steam quality so the BTU meters find their applications in those cases also. In BTU measurements flow metering is most critical. Therefore BTU metering has also been covered in this chapter. Short discussions on flow controllers often used in industrial applications are also discussed. Since the flow of material in a process plant is often related to energy flow, energy flow calculators are also covered. The metering pumps are used in industrial applications for dosing of chemicals to regulate the process in the desired manner, e.g., low-pressure (LP) dosing in feed water to maintain feed water and steam quality in boilers. The metering pump is another important issue discussed in this chapter. Many batch control processes, e.g., food and beverage plant products are bottled using dispensing machines and this is done on the basis of the volume or weight of the product. Therefore, the dispensing machine is another kind of flow device used in industrial plants and manufacturing units. Short discussions on these automatic dispensers have also been presented in this chapter. When enough straight lengths are not available for improvement of profile and swirl effect, flow conditioners/straighteners may have to be included, along with the flow meter, for accurate flow measurements. In order to complete the discussions on flow measurements, these issues shall be covered in this chapter.

From the above it can be that seen this chapter covers a variety of devices and systems which are related to and common to many types of flow measurements and controls discussed so far to give a comprehensive idea of complete flow measurement and controls in industrial and process plants. The detailed discussions on various devices and systems starts with flow conditioners.

1.0.0 FLOW CONDITIONING

By now, after going through the previous flow metering chapters, it is clear that the accuracy of most fluid flow metering depends on the flow profile of the flowing medium. Upstream disturbances (such as disturbance from a valve, elbow, etc.) have a direct impact on the profile of the flow. Flow conditioners and flow straighteners are used for flow meter, process, and pump system applications. In order to get accurate and repeatable flow measurement, flow meters require a specific amount of straight pipe run upstream and downstream from the installed location of the meter. The straight pipe runs create a swirl-free and symmetric velocity profile in the conduit to measure flow repetitively and accurately. The presence of swirl can often overpower the accuracy of integration for flow computation.

It is not always possible (in fact in most cases it is practically impossible) to keep such a large length of straight pipe. Flow conditioners eliminate the flow distortion effects of elbows, pipe expansion or reductions, valves, dampeners, and other disrupters to produce a swirl-free, symmetrical, and repeatable flow profile to the flow meter, pump, or other critical components. Therefore, flow conditioners reduce straight-run requirements to just a few diameters. A flow straightener is basically a device used to straighten medium flow. The flow conditioner is used to generate a fully developed flow profile. Flow conditioner is a generic term used to cover both flow straighteners and true flow conditioners. ISO 5167-part 1:2003 is considered as the governing standard. *In this chapter flow conditioners and flow straighteners have been abbreviated as **FC** and **FS**, respectively.* We now look at the two definitions.

1. **Concept of flow straightener and flow conditioner:** Instead of giving a definition it is better to explain flow straighteners and flow conditioners as follows:
   - *Flow straightener (FS):* Flow straighteners can be conceived of as devices that remove or have limited ability to straighten the flow and bring back the accuracy of flow measurement. This is otherwise lost due to profile distortion. It tries to replicate the orifice coefficient of discharge (flow meter) database values.

- *Flow conditioner (FC):* Devices that effectively remove the swirl component from the flowing stream while redistributing the stream to produce flow conditions that accurately replicate the orifice plate coefficient of discharge (flow meter) database values.

  The above are explanations according to AGA3 Part 2 definitions for an orifice. In order to include other metering devices the flow meter within brackets has been included because the purpose is generally the same as for other flow meters.

2. **Flow conditioning requirements:** One should keep in mind that a no-flow meter does not require any flow conditioner for its working/functioning or producing effective result. What actually happens is that due to the disturbance profile presented to the flow meter being disturbed, even if meter operates correctly, the result will be inaccurate. *Why flow conditioners?* The following are major reasons for using flow conditioners:
   - *Swirl and distortion:* Flow conditioners eliminate major pipe line swirls and distortion;
   - *Isolation:* It tries to isolate the flow meter from upstream disturbances. Therefore it is often referred to as an isolating flow conditioner;
   - *Noise:* It eliminates pulsation problems and noise;
   - *Stability:* It offers flow stability for flow measurements especially, for USFM;
   - *Balancing act:* It balances pressure velocity and flow rate accurately by running parallel tubes, and hence unloads the meter to give better accuracy [1];
   - *Short pipe run:* In view of the above issues it can drastically reduce straight pipe run requirements, i.e., shorter practicable upstream and downstream pipe runs can be used.

   Therefore one can summarize that with a flow conditioner one can take care of profile distortion, swirl effect, installation effect pulsation, and system noise.

3. **Swirl:** In the above discussions we have talked about swirl: *what is Swirl?* Swirl can be conceived of as the rotation of fluid within the conduit. It has centripetal force to heat the pipe and there may be energy loss. Swirl in a flow is mostly generated by a change in the direction of flow (due to pipe direction) and some form of restriction in the pipe faced by the flowing medium. Therefore, its impact on flow conditioner design cannot be overestimated. The impact of swirl has been discussed in detail in Section 1.3.0 of this chapter.

   In the following sections flow straighteners and conditioners based on ISO 5167 standard are discussed. Short discussions on these will also be provided for the API standard.

1.1.0 Flow Straighteners

From ISO 5167 part 1:2003 (Section 7.3.3) one gets that at each point across the pipe cross-section the ratio of local axial velocity to maximum axial velocity is within 5%. So, in order to get this one needs to eliminate swirl and flow profile distortions. As stated earlier, flow straighteners remove or significantly reduce swirl to get a better flow profile. However, it is unable to achieve total flow condition discussed above. There are a few different types of flow straighteners included in the standard and these are depicted in Fig. XI/1.0.0-1. The different types included in the standard are:

- The tube bundle flow straightener;
- The AMCA straightener;
- The Étoile straightener.

We now have brief discussions on each of the types mentioned above.

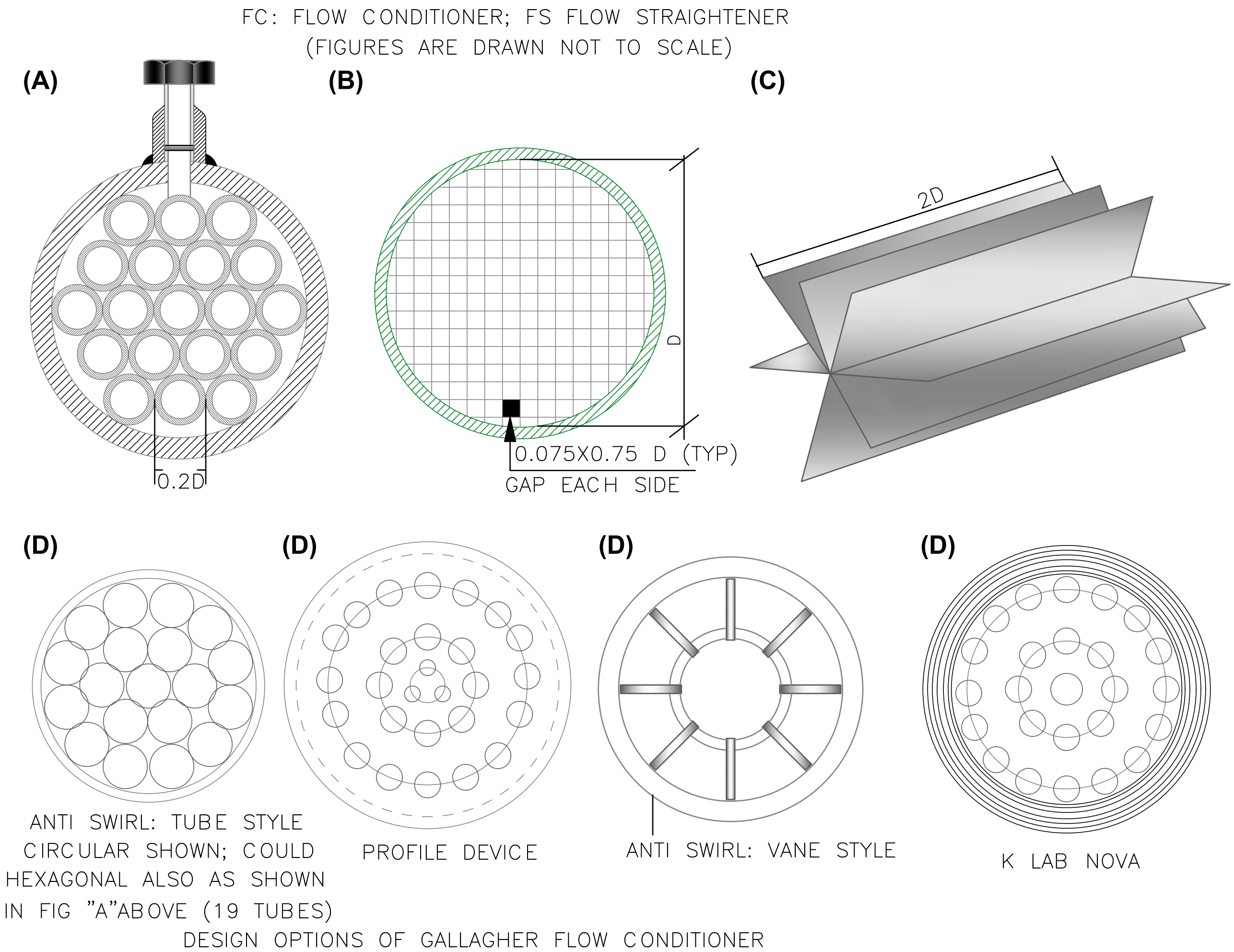


FIGURE XI/1.0.0-1 Standard flow straightener and flow conditioner. (A) Tube bundle FS: ISO 5167:2003. (B) AMCA FS: ISO 5167:2003. (C) Etoile FS: ISO 5167:2003. (D) Flow conditioner FS: ISO 5167:2003.

1.1.1 TUBE BUNDLE FLOW STRAIGHTENER

As shown in Fig. XI/1.0.0-1A, the tube bundle flow straightener consists of a bundle of parallel and tangential (to each other) tubes fixed and joined together and held rigidly in the inner surface of the pipe, as shown in Fig. XI/1.0.0-1A. There should be at least 19 small tubes in the bundle in the tube bundle flow straightener. These tubes have their axes parallel to each other, and these axes should also be parallel to the axis of the pipe to avoiding swirling. The tubes shall be arranged in such a way that there is a minimum gap between the tube surface and the pipe in the inner circumferential area. The length of the tube diameter is normally greater than or equal to $10d_t$, where the diameter of each tube is d_t. The following criteria as per standard should be followed:

1. Number of tubes should be 19 as a minimum, arranged in a hexagonal (as shown in

Fig. XI/1.0.0-1A) or circular arrangement (similar to that shown for the flow conditioner in Fig. XI/1.0.0-1D leftmost figure), so based on pipe ID diameter (D), the diameter of each tube d_t is determined.

2. Tube outer diameter $d_t \leq 0.2D$ as shown.
3. Length of tubes should be greater than or equal to $10d_t$.
4. Thickness of tubes <0.025D.
5. When tubes are arranged in a hexagonal/circular manner there will some gap along the circumference of the pipe and this gap should be at a minimum.
6. Centering spacer shall be around four (optional).
7. Overall diameter of the tube bundle flow straightener should be between 0.95D to D.

The pressure loss coefficient, K, of the flow straightener depends on the number of the tubes and their wall thicknesses. Typically for the 19-tube bundle flow straightener it is approximately equal to 0.75. Here

$$K = \frac{\Delta P_c}{0.5 \cdot \rho v^2} \qquad \text{(XI/1.1.1-1)}$$

where ΔP_c = pressure loss in flow straightener; ρ = density of fluid; and v represents the axial velocity of the fluid in pipe.

1.1.2 AMCA FLOW STRAIGHTENER

Flow straighteners at times are referred to as honeycombs. The AMCA straightener is like a honeycomb with square meshes, the dimensions of which are shown in Fig. XI/1.0.0-1B. The vanes should be very thin but should provide adequate strength. As shown in Fig. XI/1.0.0-1B, the typical gap in each side of the mesh should be 0.075D. The overall length should be 0.45D as per the standard. The pressure loss coefficient, K, for the AMCA straightener is approximately equal to 0.25 (see Eq. XI/1.1.1-1).

1.1.3 THE ÉTOILE STRAIGHTENER

As shown in Fig. XI/1.0.0-1C, the Étoile straightener has eight radial vanes at equal angular spacings, with a length equal to twice the diameter of the pipe. Like the AMCA flow straightener, here also the vanes should be very thin but with adequate strength. Similar to the AMCA flow straightener, it has a pressure loss coefficient, K, approximately equal to 0.25.

1.2.0 Flow Conditioners (True Flow Conditioners)

Flow conditioners, better referred to as true flow conditioners, not only redistribute the velocity profile to bring within the limit specified (in Section 7.3.3 of ISO 5167 part 1:2003) standard but also remove swirl significantly. In addition to a perforated plate, there are several other design variations of flow conditioners which, according to standard (ISO5617 **Part 1**:2003), are easier to manufacture, install, and accommodate. According to the standard, they have the advantage that their thickness is typically around D/8 as compared to a length of at least 2D for the tube bundle. These can be drilled from the solid, and a more robust device is produced, offering repeatable performance. The geometry of the plate is critical in determining across the plate. Geometrical shapes have an impact on the performance, effectiveness, and pressure loss. There are several variations such as:

- Gallagher (with design options) (Fig. XI/1.0.0-1D);
- K-Lab Nova (Fig. XI/1.0.0-1D);
- Zanker (Fig. XI/1.0.0-2);
- NEL (Spearman);
- Sprenkle.

These are described in the following sections.

1.2.1 GALLAGHER FLOW CONDITIONER

According to the standard, depending on the type style and design specification the pressure loss coefficient, K, for the Gallagher flow conditioner is approximately equal to 2.

There are three design options available under these types of flow conditioners. These are listed here.

1. **Antiswirl device:** An antiswirl device in tube style consists of a 19-tube uniform concentric bundle, as shown in the left-most image in Fig. XI/1.0.0-1D. The depth of the device is around 0.5D (nominal diameter of the pipe). It has a front diameter to match the diameter of the raised face. The thickness of the raised face is variable with the pipe size and is uniquely defined in the standard. Its placement with the profile device is separated by 2.5D (nominal diameter of the pipe).
2. **Profile device:** The profile device is basically a tube bundle in a 3 8 16 arrangement, as shown in the rightmost part of Fig. XI/1.0.0-1D for a Gallagher flow conditioner. Design details regarding hole sizes have been mentioned in the standards with respect to pipe ID (D) and have been reproduced as Table XI/1.2.1-1
3. **Vane style:** An antiswirl vane style has been shown in Fig. XI/1.0.0-1D for a Gallagher flow conditioner. This is similar to the other antiswirl device discussed above. Here also the thickness of the raised face is variable with pipe size and is uniquely defined in the standard. The depth of the device is around 0.125D (nominal diameter of the pipe).

TABLE XI/1.2.1-1 Design Details for Profile Device Gallagher FC

Holes	Diameter Selection	Diameter of PCD
3	Sum of area of three holes within 3%–5% pipe area	0.15D –0.155D
8	Sum of area of three holes within 19%–21% pipe area	0.44D –0.48D
16	Sum of area of three holes within 25%–29% pipe area	0.81D –0.85D

1.2.2 K-LAB NOVA

This type of design is very similar to the profile device described in Subsection 1.2.1.2, the only difference being that here there are 25 bored holes in a symmetrical circular pattern, as depicted in Fig. XI/1.0.0-1D. The plate thickness as per the standard shall be 0.125D to 0.15D (pipe ID). These are mounted with a flange whose thickness depends on the application; the outer diameter and flange face surface depend on the flange type (serration type shown here) and the application. Design details relating to pipe ID and Reynolds number are presented in Table XI/1.2.2-1 as per the standard. Dimensions are with respect to pipe ID "D." For tolerances the standard may be referenced.

TABLE XI/1.2.2-1 Design Details for K Lab Nova FC (Reynolds Number: R_e)

	$10^5 \leq R_e < 8 \times 10^5$		$R_e > 8 \times 10^5$	
Holes Numbers	Hole Diameter	PCD	Hole Diameter	PCD
Central	0.226D	Not applicable	0.186D	Not applicable
8	0.163D	0.5D	0.163D	0.5D
16	0.124D	0.85D	0.12D	0.85D

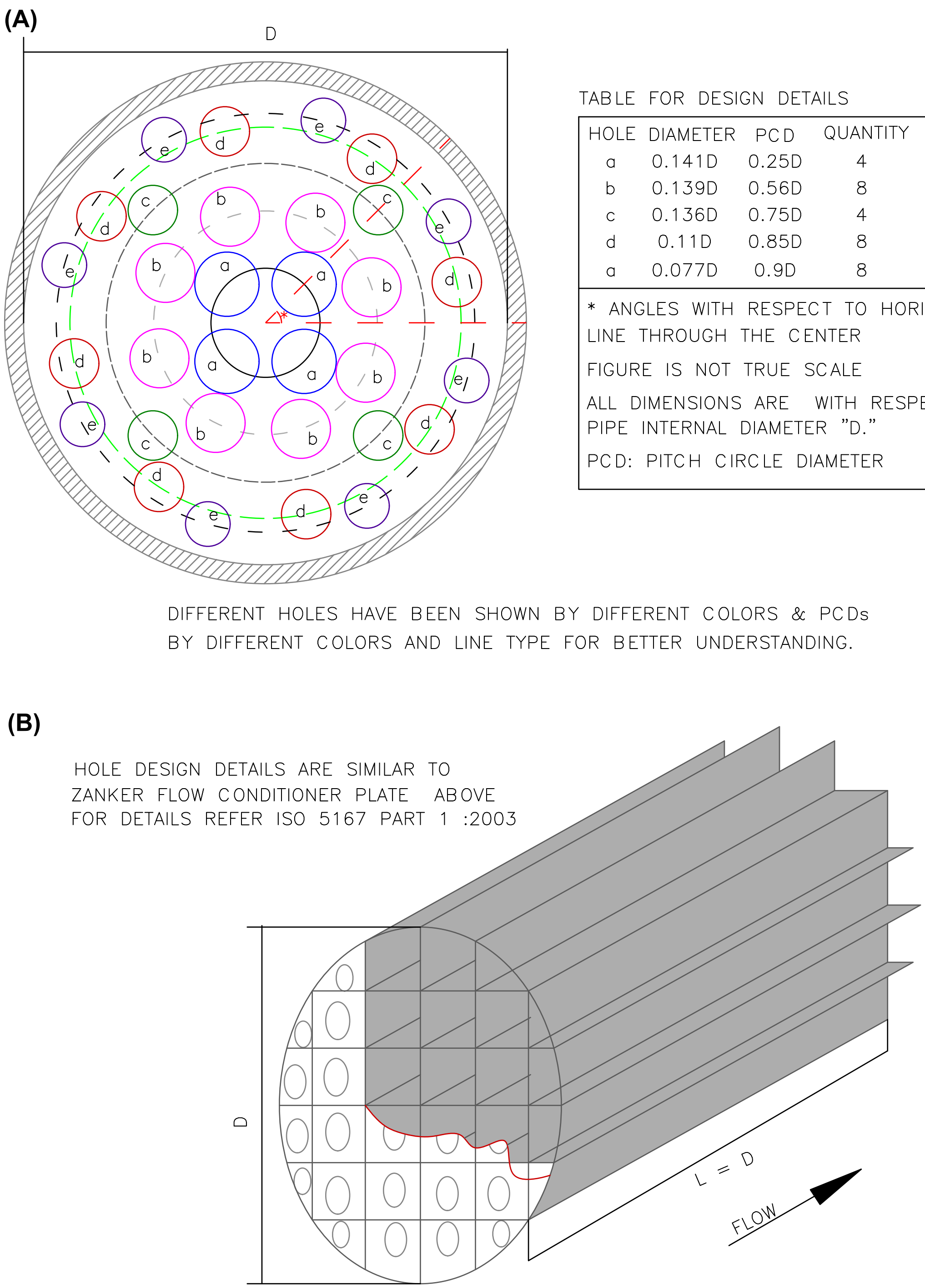


FIGURE XI/1.0.0-2 Zanker flow conditioning. (A) Zanker flow conditioner plate. (B) Zanker flow conditioner. *Developed based on ISO 5167—Part 1: 2003 (Annex C).*

1.2.3 ZANKER FLOW CONDITIONER CONDITIONING PLATE

This is one of the most popular types of flow conditioner with a special design. It is available in a plate form also. Both are depicted in Fig. XI/1.0.0-2. The Zanker flow conditioner consists of a perforated plate of holes of specified dimensions. These holes are followed by a number of channels (one for each hole) formed by the intersection of a number of plates as shown in Fig. XI/1.0.0-2B. Here also these plates should be as thin as possible but with adequate strength. The pressure loss coefficient, K, for the Zanker FC is approximately equal to 5. The Zanker flow conditioner has an egg shape, as shown in Fig. XI/1.0.0-2B. It is often referred to as the Zanker flow straightener.

Design details for flow conditioners and Zanker plates are similar, so the table given in Fig. XI/1.0.0-2A may be followed. For tolerance the standard may be referenced. The Zanker flow conditioner plate is very similar to the Zanker flow conditioner described above, with the difference being that it does not have the an egg-box honeycomb attached to the plate; instead the plate thickness has been increased to D/8. For further details the standard may be referenced.

1.2.4 NEL (SPEARMAN) FLOW CONDITIONER

This is another design with three sets of holes placed symmetrically and radially. As usual the design data are specified with respect to pipe ID (D). This is a perforated plate with thickness around 0.12D. Table XI/1.2.4-1 specifies the design details as per the standards. This should be read in conjunction with Fig. XI/1.0.0-3.

TABLE XI/1.2.4-1 Design Details for NEL Spearman FC

Hole	Number of Holes	Hole Diameter	PCD
d1	4	0.1D	0.18D
d2	8	0.16D	0.48D
d3	16	0.12D	0.86D

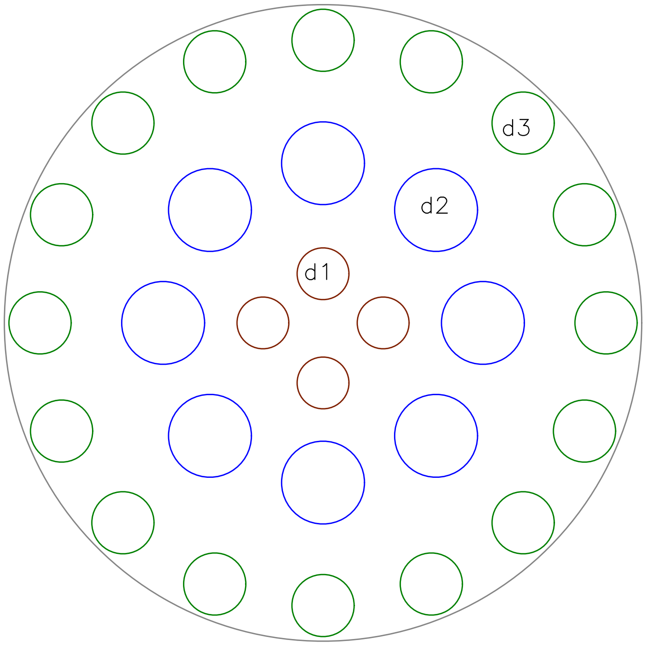


FIGURE XI/1.0.0-3 NEL Spearman flow conditioner.

The pressure loss coefficient, K, for this flow conditioner is approximately equal to 3.2.

1.2.5 SPRENKLE FLOW CONDITIONER

The Sprenkle conditioner consists of three perforated plates in series with length equal to D ± 0.1D between successive plates. The holes are preferably chamfered at 45 degrees on the upstream side to reduce the pressure loss. The pressure loss coefficient, K, for the Sprenkle conditioner is approximately equal to 11 if there is an inlet bevel, or 14 if there is no inlet bevel. For details Annex C of ISO 5167 part 1:2003 may be referenced.

1.3.0 Discussions on Flow Conditioning

There is a saying that it is easier to measure good flow with a bad meter, than to measure bad flow with a good meter. This is because of the fact that however good the meter is, if the flow profile has profile distortions, unpredictability due to swirl means—it is not possible to get reliable and accurate results from various meters, especially for DP type measurements and volumetric

measurements. In the case of a flow conditioner it has to take care of a number of issues. We now look at the impact of swirl in flow measurement.

1.3.1 IMPACT OF SWIRL ON FLOW MEASUREMENT

Swirl also has an impact on the accuracy of flow measurement. As stated earlier it is influenced by piping restrictions (installation effect) and affects various meters differently. We now look into these issues.

1. **Swirl effect:** The major effects of swirl are as follows:
   - *Profile distortion:* Swirl creates unpredictable distortions in the flow profile.
   - *Time effect:* The impact of swirl in distorting flow profile also changes with time.
   - *Energy:* Swirl has centripetal force, which can cause a complete change to the flow profile, as it can flatten or even invert the flow profile. The harder the fluid is spinning, the more energy that is pushed to the pipe walls [1].
   - *Location effect:* Swirl can cause local effects due to the location of pressure taps of the DP measurement transducer or the location in USFM adding to or subtracting to local path velocity [1].
2. **Installation effect:** Various pipe and instrumentation fittings such as tee, elbow, expander/reducer, valves of different kinds, probes, restrictions, etc. in the way of medium flow directly affect swirls. Each of these fittings, their location orientation, and operations have different effects on swirl. For this reason, for different fittings there are different straight length requirements, e.g., 90 degrees. Elbows in the same plane and at different planes have different straight length requirements. Also for this reason, temperature probes for density compensations are recommended at the downstream of the flow-measuring device. The same instrument at different locations can perform differently if the installation effect is not taken care of properly.
3. **Meter types:** Each meter and meter type responds differently to the effects of swirl and flow profile distortion. Volumetric flow-measuring instruments including DP type, turbine, vortex, electromagnetic, and ultrasonic, to name a few, are affected by swirl and the size of the effect varies with type. For this reason each type has different straight length requirements, even for the same type of fittings in the pipe. As for deriving the flow-measuring formula for each of these types of meters, good flow profiles are assumed, so they look for a good flow profile without swirl effect. In the real world the same can happen, so straight lengths are recommended to get better accuracy. Flow conditioners try to straighten the flow profile and minimize the swirl effect and present good flow to the meter with shorter lengths of straight pipe run.

1.3.2 SWIRL EFFECT ON SOME SELECTED METERING TYPES (VOLUME FLOW)

Through studying the relevant literature, short discussions on swirl effect on different meter types have been presented in this section. For discussions only a few selected types have been covered.

1. **Orifice (head type flow measurement):** In restriction type flow elements such as orifice, flow nozzle, and Venturi, swirl can change the pressure differential that is being measured. Also, such a swirl effect on pressure measurement will be influenced by the location of pressure taps. In order to get some idea of how swirl can affect pressure measurement in restriction type flow elements, Table XI/1.3.2-1 is presented. Data in the tables are practical data and have been taken from CPA orifice data (part) [1] (courtesy: CPA).
2. **Pitot tube:** As seen in Chapter II, Pitot tubes consist of two hollow tubes, one measuring the impact pressure and the other measuring static pressure. On account of swirl, orifice

TABLE XI/1.3.2-1 Swirl Effect on Pressure Measurement for Orifice Plate

Swirl (Degree)	Velocity (m/s)	Bulk Density	DP (Pa)
0	15.24	36.84	140,011
20	15.24	36.74	119,728
45	15.24	36.68	62,363

plate pressure measurement is disturbed, but with flow conditioner a swirl-free flat velocity profile can be obtained to get the ideal flow regime. It is a similar case for averaging type Pitot measurement also.

3. **V cone meter:** This is often referred to as a self-conditioning element. It has a unique geometry that forces flow to the outside in the pipe [1]. It has a high-pressure tap in a similar place as in restriction flow elements, like orifice or Venturi, but a low-pressure tap at the center. A V cone by its constructional geometry is immune to the installation effect and demands shorter straight length when compared with DP type traditional measuring instruments. However, for V cone meters, a common disturbance found in piping configurations is the single 90 degree elbow and close coupled double 90 degree elbows out-of-plane. From the literature it has been found that "McCrometer's tests indicate that within the tested beta ratio range, the V-Cone meter can be installed close—even close coupled—to either single or double elbows out of plane without affecting the stated accuracy of the meter more than 0.3%" (*http://www.iceweb.com.au/Flow/vcone.htm*).
4. **Magnetic flow meters:** Magnetic flow meters measure voltage proportional to flow rate. Upstream flow disturbances and inadequate straight run adversely affect performance. Naturally there will be requirements of flow conditioners to circumvent the situation with practicable straight length. Electromagnetic flow meters find wide applications in sewage applications where it has often been found that flow meters are placed too close to pumps in sewage lift stations. In such cases manufacturers have come out with elbow flow conditioners, e.g., 90-degree angle tab-type Vortab elbow flow conditioners. Like other flow conditioners, elbow flow conditions also eliminate the flow meter upstream piping requirements by conditioning the flow stream into a flow regime, mimicking adequate straight run, and these have been tested in the laboratory also for assured performance [2].
5. **Turbine meters:** Swirls are create due to rotation of fluid, so fluid rotation in the direction of the meter rotation or in the opposite direction to the meter rotation, would cause the meter to under or over register, respectively, from a flow point of view. However, dual rotor design has less of an effect on this account. As seen in Chapter V there are turbine meters with built-in flow straighteners at the inlet to get a better flow profile for the meter. However, for better results, i.e., reliable, accurate, and repeatable flow measurements, flow conditioners are used to get an ideal flow profile as far as possible by eliminating rogue vortices from crossing the meter.
6. **Ultrasonic flow meter:** Nonaxial component of swirl results in inaccurate flow measurement. During measurement, the transducer also senses and transmits a noise pulse. It also senses changes in axial velocity due to the nonaxial part of the swirl in the fluid. This means flow rate computation by transit time method is affected by velocity disturbances within the pipe, by slowing or speeding up the pulse. A similar effect can also be noticed with the other type also. This effect to a certain extent can be minimized by using multipath nonplaner configuration in a criss-cross method swirl cancellation from the impact of over and under reading. This may

improve but cannot always guarantee accurate measurement. Tube bundle conditioners provide long channels aligned with flow axis and remove swirl. These also give less pressure loss. In view of this tube bundle, flow conditioners are often used. However, on account of difficulty in manufacturing and the chances of wrong alignment of tubes, plate type conditioners such as Zanker plates are often offered. As, they offer press loss coefficient K > 2.

1.3.3 PRESSURE DROP AND STRAIGHT LENGTH ISSUES

Pressure drop is an important criterion in selecting the type of flow conditioners. Most plate type flow conditioners have a K factor of approximately 2, especially in natural gas applications. Tube bundles on the other hands as has been seen, have a K factor in a range closer to 0.75−1.5. Pressure losses through fittings can be complicated, depending on the application [1]. Flow measurement and flow conditioning in liquids are effectively similar as in gases and almost all fluids flow measurement gets benefit from flow conditioning. However, in certain cases pressure drop is a big issue, especially when debris is present. Eliminating flow conditioners does not mean elimination of debris. Therefore, for debris, filters/strainers need to be used (this may again increase the pressure drop), otherwise it may damage inline probes or expensive mechanical parts. Pressure losses through fittings can be complicated, depending on the application. Therefore, one needs to consider that pressure drop is obviously an important issue but for bigger issues flow conditioners should be accommodated for accurate measurement. Also, the flow conditioner will not be the most significant obstruction. From this the final take is that, when necessary, flow conditioners are to be used with a flow meter for better results. Associated with pressure drop and profile distortions the requirements for straight lengths are also connected. AGA also provide guidelines on meter run compliance for which the following standards may be referenced:

- AGA 3/API 14.3—Orifice Meter Measurement;
- AGA 7—Turbine Meter Measurement;
- AGA 9—Ultrasonic Meter Measurement;
- AGA 11—Coriolis Meter Measurement.

1.3.4 SOME API REQUIREMENTS

The American Petroleum Institute (API) and American Gas Association are closely associated with the oil and natural gas industries and they have certain norms and standards. To complete the discussions on flow conditioning it is necessary to get a brief idea of their guidelines and practices.

1. **Straight length requirements and representation:** Let us take an example from the revised API 14.3/AGA 3—Part 2, regarding typical straight length representation with and without a flow conditioner. A typical such arrangement with a flow conditioner is depicted in Fig. XI/1.0.0-4 to get an idea of how the same is to be arranged. This figure has been reproduced from the American Gas Association (AGA) 3.

   The standard provides the standard required minimum installation lengths, UL and DL, for meter tubes with no flow conditioners in Table 2-7. Similarly, with 1998 Concentric 19-Tube Flow Straighteners, the requirements of straight lengths are provided in Tables 2-8a and 2-8b.

   Based on this, one could decide UL1/UL2 and DL, as shown in Fig. XI/1.0.0-4 (Figure 2-6 of the standard).
2. **Tube bundle requirements:** As per the AGA, tube bundles are allowed under the following conditions:
   - *Tube quantity:* Only 19 tube uniform concentric tubes;
   - *Configuration:* All tubes must touch one another;

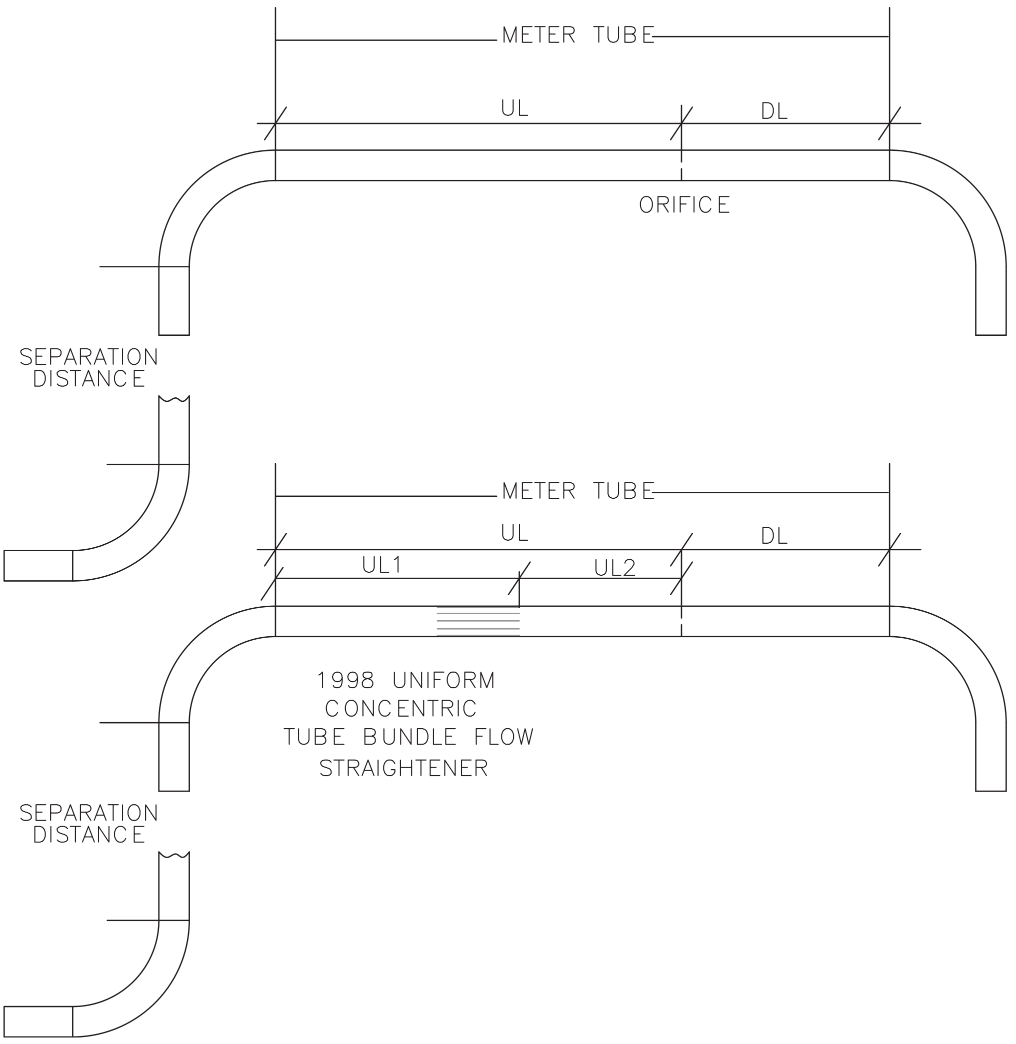


FIGURE XI/1.0.0-4 Meter layout (as per guideline from AGA 3).

- *Welding:* Tubes must be welded together;
- *Dimensions:* OD (overall diameter) > 0.95D; tube wall thickness t < 2.5% of D.

3. **API type approval requirements:** The following disturbance tests are the API requirements:
   - *Elbow test:* Two 90 degree elbows in perpendicular planes;
   - *Gate Vale:* Gate valve 50% closed;
   - *Swirl:* High swirl.

   With this, the discussion on flow conditioning is concluded and we now investigate process transmitters used for flow measurements with different flow element types.

2.0.0 FLOW TRANSMITTERS (DPT AND MVT) AND CONVERTERS

Based on the quantity of medium of flow, in DP/head type flow measurements, flow elements create differential pressure. This differential pressure must be measured and evaluated to arrive at the quantity of flow. The flow measurement in this method is basically volumetric type flow measurement. Variations in temperature and pressure would affect the density of the medium and hence the flow. Also, for mass flow calculations it is necessary to measure pressure and temperature to compute the mass flow.

Therefore, for complete flow measurement discussions it is essential to gather some knowledge on measurement of differential pressure by DPTs. Also, one needs to know the measurement of temperature and pressure and associated pressure transmitter types. From the above discussions it transpires that in order to completely get flow by DP/head type measurement, one needs to measure three parameters—DP, pressure, and temperature. The pressure transmitter has been described in Sections 4.1.4 and 4.2.0 of Chapter III, which may be referenced for details and so will not be repeated here. This section elaborates DPTs. To complete the discussions on flow measurement, brief discussions on the temperature transmitter are also given. However, the actual flow computation is done by a flow computer (Section 5.0.0), discussed later in this chapter. Nowadays, special smart transmitters, which can measure all the three parameters (DP, pressure, and temperature) described above, are available. These are called ***Multivariable transmitters***. In this section, detailed discussions on the same shall also be covered. In order to complete the discussions, installation, calibration, and testing of these transmitters are covered.

2.1.0 Basic Transmitter Theory, Technologies and Selection

Pressure transmitters and differential pressure transmitters are basically different in the ways that measurements are accomplished. However, the basic theories and principles of operation of pressure transmitters and differential pressure transmitters are the same. The only difference is that former one is a single pressure measurement (SPM), i.e., the actual pressure measurement is in one chamber only, while the latter one, i.e., DP measurement, is dual pressure measurement (DPM), i.e., the actual pressure measurement is carried out in two chambers in differential modes. To be precise, all kinds of pressure transmitters are basically differential pressure transmitters with high-pressure (HP) and low-pressure (LP) measuring chambers. This will be clear from the following measuring methods:

- *Differential pressure (DPM):* HP: Measuring pressure (hi); LP: Measuring pressure (lo);
- *Gage pressure (SPM):* HP: Measuring pressure; LP: Atmospheric pressure;
- *Draft (pressure) (SPM):* HP: Atmospheric pressure; LP: Measuring pressure; (-)ity shows how much it is below atmospheric pressure, e.g., furnace pressure $-5''$ (-125 mm) H_2O means that the actual pressure at the furnace is below atmospheric pressure by $5''$ (-125 mm) H_2O;
- *Absolute pressure (SPM):* HP: Atmospheric pressure; LP: Fully/perfect vacuum (reference chamber);
- *Vacuum (pressure):* Same as the draft transducer mentioned above only the range is different and the expression of pressure may be different, e.g., $10''$ (250 mm) H_2O vacuum means $-397''$ (9925 mm) H_2O absolute or 0.1 kg/cm^2A condenser vacuum.

Thus it can be seen that by leaving one chamber open to the atmosphere or connecting to a perfect vacuum a differential pressure is converted into pressure (SPM) by transmitters of different categories. There are a number of technologies based on which differential pressure transmitters are developed. As is clear from the above discussions, in working principles all transmitters are basically DPT, so various operating principles discussed in Subsection 4.1.1.4 of Chapter III, along with Fig. III/4.1.1-2, are equally applicable for DPTs and MVTs which accommodate measurements of DP, absolute pressure, and temperature with the help of an external temperature element like RTD in a single packaging unit. Thus, in MVTs we have DPT and PT and a computation unit where the external signal from the temperature probe is applied. Working principles of DPTs and PTs are the same and have been discussed in Subsection 4.1.1.4 of Chapter III which may be referenced.

2.1.1 SIGNAL TRANSMISSIONS AND SMART TRANSMITTERS

Let us now concentrate on how the signal transmission takes place. The discussions presented here are also applicable to all transmitter types, e.g., process transmitters, temperature transmitters, including PTs discussed in Chapter III.

1. **Current signal transmission:** In connection with the discussions on pressure transmitters in Section 4.1.1 of Chapter III it has been noted that there would be secondary electronics in the transmitter to amplify the weak signal of the sensor and filter units to filter out noise as far as possible, so that the signals can be sent long distances without being degraded by noise. These transmitted signals are meant to drive secondary instruments, such as inputs of PLC/DCS, indicators, recorders, totalizers, and controllers. Electronic process transmitters used deploy current transmission because, in current transmission it is possible to transmit signals over a long distance without loss. In the case that voltage signal is used there will be loss due to voltage drop over a long distance. It is not that in current transmitters there is no loss, because of stray capacitances in cable there can be loss of current signal, but that it is much lower than the voltage drop due to cable resistance. Also, it can be minimized by using screened cable. In signal transmission live zero, i.e., 4 mA bias, is used so as to distinguish zero signal from a cable cut. There are two ways for current signal transmission, these are described here.
   - *Four-wire transmissions:* In four-wire transmitters, two wires are used for instrument power and the other two wires are used for signal transmission. This type of signal transmitter has become more or less obsolete for quite some time. If these are used at all, they are used in special cases for remote areas where there is no commercial power available and measurement is carried out by battery, e.g., special cases of some battery-operated transmitters in remote gas pipelines.
   - *Two-wire transmissions:* Two-wire transmissions are designed to provide a 4–20 mADC signal. Most analog electronic process transmitters and smart transmitters with HART protocol use this mode of transmission where both the signal from the transmitter and power supply to the transmitter use the same set of two wires in a loop with load impedance.
2. **Smart transmitter:** In smart type transmitters there is built-in intelligence in the form of a processor and associated memory in embedded electronics. Such embedded systems make it possible to integrate the systems (and also can support field bus). Initially in smart transmitters embedded electronics were with the secondary electronics so that it was possible for smart transmitters to transmit both digital and analog signals over the same two wires, i.e., the digital signal is superimposed over a 4–20 mA signal. HART based on Bell 202 FSK standard digital communication enjoys the most popularity. Digital signal transmission offers a number of additional facilities including but not limited to the following:
   - *Signal output:* Faster and more accurate signal output;
   - *Two-way communication:* Two-way communication;
   - *Remote actions:* Remote calibration and configuration;
   - *Diagnostics:* Extensive diagnostics;
   - *Storage of data:* Ability to store configuration data.

   With further development in embedded electronics now intelligence has been included not only at the secondary electronics but also included in sensors electronics. With the help of the sensor electronics it is possible to make sensor compensations (e.g., temperature important for some sensors), and it can store characteristics curve envelopes from the factory and

based on actual field conditions, the sensor can adjust it with the required characteristic condition to produce more accurate output. Smart transmitters of both forms support hand-held communicator/configurator of different versions with different capabilities. With the help of HART protocol it is possible to communicate and connect a few transmitters by one two-wire loop, as transmitters are addressable. However, on account of load and other limitations not too many transmitters can be in a single loop. HART protocol is the most important protocol used in smart transmitters, but there is another type—the BRAIN protocol used in Yokogawa EJX110A DP transmitters. Wireless technologies have been applied for HART transmission also i.e. wireless HART are now supported by process transmitters. For further details, chapter VII in second revision of [8] may be referenced. These are also available for use in hazardous area applications. 3051 series of Emerson or 2600 series of ABB are examples of these modern smart transmitters.

3. **Fieldbus communication:** In addition to bringing intelligence to sensors and secondary electronics, there have been great developments in signal transmission and communication also. The introduction of the fieldbus concept with transmitters is really a great leap, not only for including more and more transmitters in the two-wire loop, but it is possible to integrate intelligent control systems directly with the fieldbus. Like HART, wireless fieldbus is also possible. For further details, chapter VII in second revision of [8] may be referenced. As fieldbus systems have different layers, it is possible to integrate a field system and a control system along with plant computers. There are several fieldbus systems, e.g., Foundation fieldbus, Profibus, etc. A detailed discussion on fieldbus communication has been included in Appendix VII. The major advantages of the fieldbus include but are not limited to the following:
   - *Relocation of control function:* Relocation of control functions to the field device;
   - *Direct communication:* Possible direct communication between a sensor and a control resulting in direct reliable control for smaller loops avoiding a complex centralized control system;
   - *Digital transmission:* Better digital signal transmissions, reducing traffic in the main network communication highway.

   However, in certain cases limitations may arise from the number of instruments in each segment/loop. These are available in safe communication mode for use in hazardous area applications also.

2.1.2 TRANSMITTER MEASUREMENT LOOP

As shown in Fig. XI/2.1.2-1, modern transmitters form a two-wire loop for complete transmission of output signal to the secondary instrument loop along with a configurator.

The loop shows that there is one power supply in series with the secondary/receiver instrument (which could be DCS/PLC/receiver instruments, etc.). Normally the power supply for the loop is supplied from the connected secondary/receiver device or system. In the case of a smart transmitter, the configurator can be connected parallel to the main measuring loop to communicate with the digital FSK signal. Many of the transmitters are provided with a local indicator as shown in the loop. In addition to these, transmitters are provided with test points for a 4–20 mA test loop. The power supply can be optionally grounded also. There can be one internal ground for the loop as shown in Fig. XI/2.1.2-1. Now we look into the details about the loop power supply, load driving capability, and response time.

1. **Power supply:** Two-wire transmitters need a certain minimum voltage to operate.

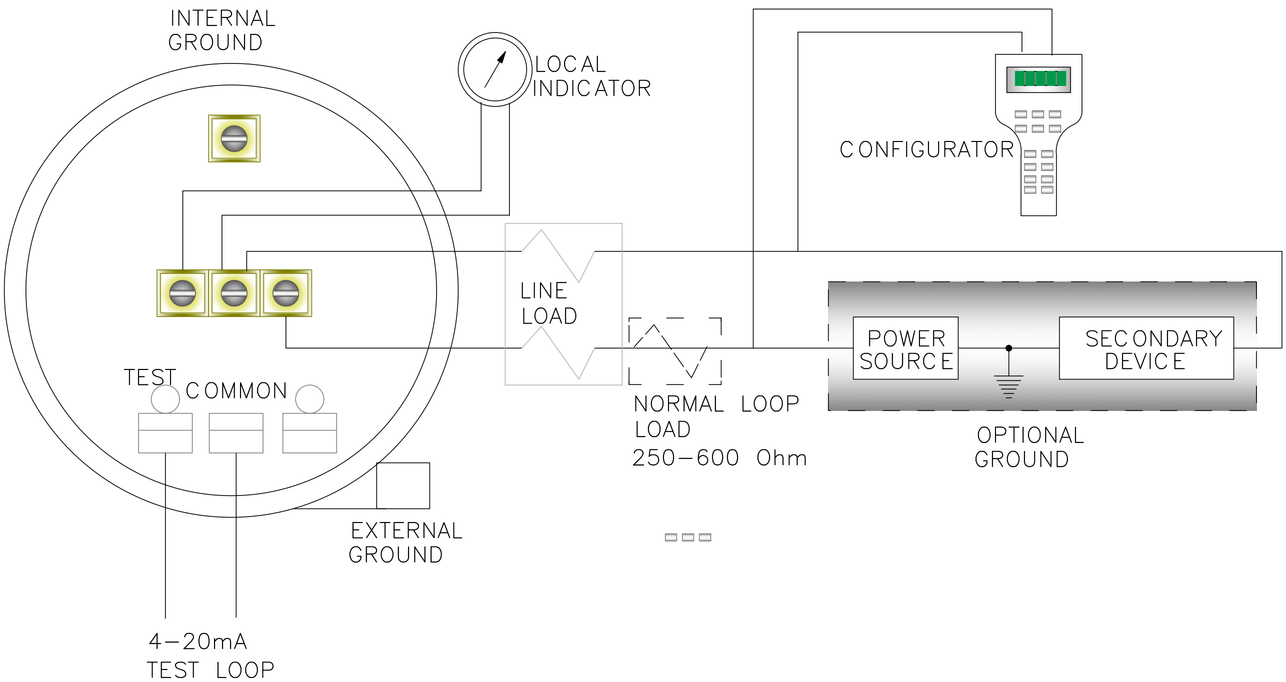


FIGURE XI/2.1.2-1 Transmitter loop (typical).

The typical value is 12 VDC. The standard transmitter operates on 10.5–42.4 VDC, with no load. The upper value limit is there from CSA. Some transmitters can also operate up to 55 VDC (e.g., ABB). The typical and normal power supply is 24 VDC (between 19 and 30 VDC).

2. **Load resistance:** Considering typical minimum 12 VDC, one can get a maximum load from a minimum typical voltage at the maximum driving current, i.e., 12 VDC/0.02 A. Most transmitters can drive a normal load from *250 to 600 Ohm.* Here 250 Ohm is the minimum loop resistance required. While considering loop resistance one has to take care of line resistance surge protector resistance (if applicable). Thus, for a loop resistance of 50 Ohm, surge protection resistance as 75 Ohm, and minimum loop load 250 it works out at 375 Ohm. Therefore, the loop is capable of accepting 600 − 375 = 225 additional load at 12 VDC. With an increase in power supply, the load resistance capability increases. With output meter and communication means, namely, HART and fieldbus, minimum power supply requirements vary. Typical load resistance versus power supply variation for HART has been shown in Fig. XI/2.1.2-2A. For Emerson the maximum load driving capacity is 1387 Ohm at a maximum voltage of 42.5 VDC (HART). Theoretically, the ABB transmitter can accept power supply up to 55 VDC, and load driving capacity could be 2150 Ohm.
3. **Response time (smart transmitter):** The response time of the transmitter has two components: dead time T_d and time constant T_c. Dead time indicates the time during which there is no change in output for a step change in input. Time constant indicates the time taken for ∼63% change in output. Typical such response times for HART (of Emerson 3051 transmitter) have been shown in Fig. XI/2.1.2-2B. Typical response times as per IEC 61298–1 definition are around 150–180 ms, including a dead time typically of around 50 ms and time constant of 100–140 ms. These are some typical data from a reputed manufacturer. For actual values the manufacturer's data sheet for dynamic performance data should be checked.

We now look into various components and accessories for transmitters.

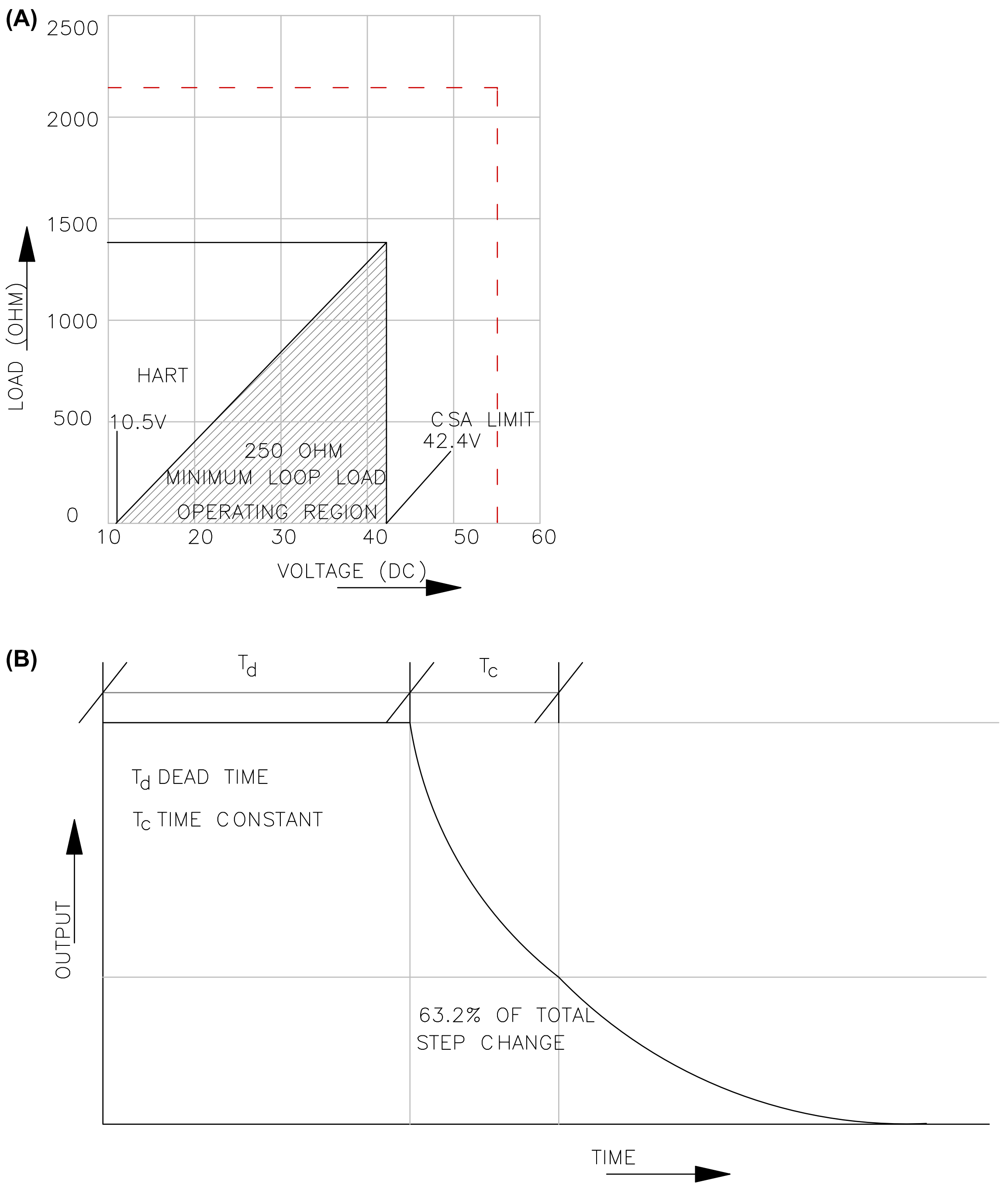


FIGURE XI/2.1.2-2 Transmitter load and response. (A) Transmitter load with supply voltage. (B) Transmitter HART response time. *Developed based on Rosemount 3051 (AUG 2016). Courtesy: Rosemount.*

2.1.3 TRANSMITTER COMPONENTS AND ACCESSORIES

Process transmitters (DPTs, MVTs) generally consist of two main parts: a sensing element (and sensor electronics), which is in direct or indirect contact with the process, and a secondary electronic package. The entire transmitter can be divided into three sections:

- Lower section comprising the process flange, etc.;
- Mid section comprising the sensor;
- Top part to house the secondary electronics.

1. **Various part details:** Detailed list of major components of process transmitter have been given in Table III/4.2.1-1, where major components of DPT/PT may be referenced. We now look into a few other components which are not often used with transmitters
2. **Remote seal:** Remote seals are used for various applications where direct use of transmitters may not be permissible otherwise. These are used for the following cases:
   - *Temperature:* Temperature limit way beyond the operating range of the transmitter;
   - *Corrosion:* Corrosive fluid with a chance of transmitter damage;
   - *Plugging:* Possibility of impulse lines get chocked due to the presence of solids;
   - *Viscosity and flowability:* Highly viscous fluid;
   - *Solidify:* Chances of solidification;
   - *Physical means:* To locate the transmitter in a suitable place for proper maintenance and measurement.

     Remote seals are normally connected by flanges. Remote seal consists of a stem, a seal diaphragm with a membrane connected through a capillary to the flanged chamber of the transmitter, and incompressible filling fluid (e.g., Silicone oil). The measured pressure is transmitted through the filling fluid to the transmitter. For proper functioning of the system the proper response time of the remote seal is very important.
3. **Valve manifold:** These are block and bleed valves. Valve manifolds used with DPTs/MVTs can be three- or five-valve manifolds. Three-valve manifolds comprise two isolating valves and one equalizing valve. In five-valve manifolds, there are two additional valves for the line drain. These are made from carbon steel or stainless steel. This is not a part of the transmitter but is used as an accessory for the installation of transmitters. Equalizing valve in three- or five-valve manifold plays very important role in connecting the transmitter into process line. After equalizing pressure in two limbs, isolating valves are operated to avoid pressure shock in any limb.

2.1.4 MULTIVARIABLE TRANSMITTERS

With the tremendous advancement of embedded electronics technology and microcontrollers the computation capabilities of transmitters have increased many fold. These made it possible to completely integrate complete flow computation into a single device. From Chapter I, it has been noted that for accurate flow computation, especially for compressible fluids, it is necessary to compensate for changes in density of the fluid under operating conditions. In order to do so, it is necessary to measure operating pressure and temperature, in addition to DP measurement. For this not only multiple instruments are necessary but also there will be multiple perforations in the pipe. This method suffers from the following drawbacks:

- Need for three transmitters (pressure, DP, and temperature);
- Multiple holes in the pipe lines with a greater chance of leakage, as well as of profile disturbances;
- Capital cost for three sets of transmitters;
- Cost of flow computer.

Nowadays, multivariable transmitters measure differential pressure and absolute (or gage) pressure from a single sensor and process temperature from a standard temperature probe. Therefore, in the case of MVT, only tapping for DP measurement and temperature probe will suffice. From a functional point of view MVT comprises there transmitters: DPT, pressure transmitter, and temperature transmitter. MVTs have built-in flow computation power to carry out the dynamic calculation of fully compensated mass or volume flow rate for gases, steam, and liquids [3]. MVTs are now available with an integral orifice, Pitot tube, and average Pitot tube versions also.

Various features and characteristics discussed above in Section 2.1.1 through 2.1.3 are also applicable to MVTs.

With this the discussion on transmitter theory comes to an end and we now investigate more details about process transmitters.

2.2.0 Material Selection

Prior to starting the discussions, it should be noted that material selection is one of the most important issues for all the instruments with the varied nature of process materials. ***Depending on applicability material characteristics can be utilized in the selection of material for all other instruments as well.*** This is equally valid for DPTs, MVTs (discussed in this chapter), and PTs (discussed in Chapter III, Section 4.0.0). In material selection both the manufacturer and the end user need to coordinate for better results. This is because the process is better known to the end user. In certain processes, under normal operating conditions, the temperature may be low but under abnormal conditions the transmitter can shoot up to a very high temperature. Apparently stainless steel can be used for sea water, but when it goes above 45°C there will be corrosion due to pitting. Also, for food beverage industries, special care for need to be taken for material selection, including the fill fluid, so that in the case of breakage in the capillary food is not contaminated. It is the user's responsibility to make a careful analysis of all process parameters when specifying materials [3].

2.2.1 WETTED PARTS

Based on the applications, there is a wide range of materials which can be used for various parts that come into contact with the process fluid. Most transmitters nowadays use a diaphragm and process flange and from there pressure is sent to the sensor through the filling fluid. Thus not too many parts of DPTs, MVTs, or pressure transmitters in that sense really fall under wetted material. We start the discussion with commonly used wetted materials. Major wetted parts of transmitters include: diaphragm, cover flange, process connector, capsule gasket, and vent/drain plug, etc. It is recommended that both the process engineer of the end user and the manufacturer's representative involved in the selection of materials.

1. **Stainless steel (316L, cast steel CF 8M; also PFA lining):** Stainless steel 316 L SST is a very common and standard material. This offers good corrosion resistance to the materials which include but are not limited to the following:
   - Low concentrations of nitric acid and most salt solutions;
   - Alkaline solutions;
   - Organic acids and compound (limited temperature);
   - Halide salts (fluorine, chlorine, etc.);
   - H_2S in oil production [3];
   - Boiler steam/water.

   These are available with NACE certifications. Often they are used with a PFA coating, such as in remote seals for corrosive applications. These are mainly used for capsules, capsule gaskets, drain vent plugs, process flanges, adapters, mounting brackets, and sensor housing.

   Cast steel ASTM CF 8M has applications in cover flanges and process connectors, which can be of SS316L also.
2. **Monel (Ni6733Cu):** These are very much suitable for oxidizing acids, such as hydrofluoric, sulfuric, and phosphoric acids and sea water. Aluminum fluoride, potassium carbonate, and sodium sulfide should not be used in gas applications with hydrogen due to gas penetration. They are used in process isolating diaphragms, sensing capsules, process flanges, adapters, plugs, and drain vent valves.
3. **Hastelloy (Ni54 Mo 16 Cr 16):** Within corrosion applications, Hastelloy alloys are often chosen due to their relatively attractive price/performance ratio. There are several Hastelloy alloy categories, referred to as Hastelloy B, C, G, and X. Of these C (also B) is mainly used. Within Hastelloy there are different grades, such as C4, C276. Hastelloy offers very good resistance against most alkalis, organic compounds, some oxidizing acids, acidic salts. At moderate temperatures Hastelloy C withstands hydrochloric and sulfuric acids in most concentrations [3] and is used in process isolating diaphragms, sensing capsules, process flanges, adapters, plugs, and drain vent valves.
4. **Tantalum:** Tantalum is very good for most acids, chemical solutions, and organic compounds including liquid metals, hydrochloric, hydrobromic, boiling hydrochloric, nitric,

phosphoric, and sulfuric acids. However, its performance in strong alkalis is poor. This is quite costly so is only used for thin process diaphragms.

2.2.2 NONWETTED PARTS MATERIALS

There are several materials used in different parts of transmitters.

1. **Housing:** The housing is mainly made up of:
   - Low-copper cast aluminum alloy with corrosion resistance properties (as applicable, such as in sea water application);
   - Aluminum polyester resin with powder-coated paints or with epoxy coating;
   - 316 SST;
   - *Lower housing:* 316SST, alloy C276.
2. **Bolts and nuts:** B7 carbon steel, 316L stainless steel bolts and nuts.
3. **Gasket/cover O-rings:** Buna-N, fluoro-rubber (optional: Viton, PTFE—not suitable for frequently changing temperature), EPDM black.
4. **Fill Fluid:** Silicone oil DC200 (up to 200°C) [3]. When the temperature is higher other low viscous fluids can be used. In oxygen services silicone fluid *cannot* be used due to being a fire hazard, hence inert fluids are used. In the case of food and pharmaceutical applications, toxic materials cannot be used. For special applications it is recommended that the end user discuss with the manufacturer the choice of fill fluid.

2.3.0 Performance Details

Prior to moving on to the discussions on the performance of various parameter, it is better to recapitulate the discussions on range and span defined in Section 1.2.1 of Chapter I. During the discussion it can be seen that the accuracy of instruments are specified as, e.g., 0.04% FSD, also specifying the turndown as 100:1 or even 400:1. This is confusing. Therefore, it is essential to study the complete manufacturer catalog to know that the guaranteed accuracy is ***never*** meant for the entire turndown ratio, instead it is specified for a specific turndown (TD) ratio, which in most cases is <10:1 TD.

We now see how accuracy is defined by various manufacturers to eliminate the confusion discussed above.

2.3.1 ACCURACY AND ITS SIGNIFICANCE

A general discussion on accuracy has been elaborated on in Section 1.2.1 of Chapter I in the case of transmitters (applicable for DPTs, MVTs, PTs). Here it is worth noting that all the data and definitions, in the following discussions, are based on data from reputed manufacturers of process transmitters. Some define this as described below.

For TD from 1:1 to 10:1:

$$\text{Transmitter accuracy} = \pm 0.04\%\ \text{FSD} \tag{XI/2.3.0-1}$$

For TD > 10:1:

$$\text{Transmitter accuracy} = \pm(0.04 + 0.005 \times \text{URL/Span} - 0.05)\% \tag{XI/2.3.0-2}$$

The take out from this is that as long as the TD of the transmitter is within 10:1 guaranteed accuracy is possible. However, when the TD is more than 10:1, i.e., if for the transmitter the minimum span is, e.g., 0.06 bar and the URL is 6 bar and selected span is 0.5, making TD < 10:1, an accuracy of 0.04% FSD is assured. However, if the selected span is, e.g., 0.7 bar then accuracy is not guaranteed as at this point accuracy is a function of URL. The higher the URL, the greater will be the value, i.e., more inaccuracy. The constants in the accuracy computation given in Eq. XI/2.3.0-2 will vary with the manufacturer's data, e.g., the same for another manufacturer could be TD > 10:1:

$$\text{Transmitter accuracy} = \pm(0.015 + 0.005 \times \text{URL/Span})\% \tag{XI/2.3.0-3}$$

This change in value of constant may vary from model to model and may vary for different applications. Similar variations in overall accuracy and TD also may change with the *sensor type* or *URL* of the same manufacturer. Therefore it is always advisable to check with the manufacturer's data sheet for a particular model and sensor type (code) which is uniquely defined by the manufacturer in the data sheet along with the minimum span and URL. For flow transmitters, i.e., DPTs/MVTs with integral orifice plate, Pitot tube and average Pitot (Annubar) are defined slightly differently. Since in these cases it is the flow rate not the DP that is the governing factor these are defined as in this example:

For flow TD 8:1

$$\text{Accuracy} = +1.8\% \text{ of the flow TD} \tag{XI/2.3.0-4}$$

At times for an integral orifice these are even categorized for different beta ratios, we take this as an example:

For $0.2 < \beta < 0.6$.

For flow TD 8:1:

$$\text{Accuracy} = +1.75\% \text{ of the flow TD} \tag{XI/ 2.3.0-5}$$

Similarly,

for $0.6 < \beta < 0.8$.

For flow TD 8:1:

$$\text{Accuracy} = +2.10\% \text{ of the flow TD} \tag{XI/ 2.3.0-6}$$

2.3.2 OTHER MISCELLANEOUS EFFECTS AND RESPONSES

1. **Static pressure effect (applicable for DPTs and MVTs):** Static pressure influences both zero as well as span error. This is a function of the sensor type and is expressed as % of URL and span.

   This is given in Table XI/2.3.2-1 collecting data from a reputed manufacturer.
2. **Ambient temperature:** Ambient temperature influences the performance of the transmitter causing drift. This is expressed as for TD 15:1 per 20K change between the limits of −20°C to +65°C expressed as % URL and % span.
3. **Stability:** This indicates how long the specified performance is assured, i.e., drift of performance over time. It is expressed as % of URL over a time period, e.g., 0.1% URL for 36 months.
4. **Vibration:** This is as per the IEC 61298−3 definition, expressed as % URL (0.1%).
5. **Electromagnetic compatibility:** Standard: EN550011 Namur recommendation.
6. **Pressure equipment directive (PED):** As per applicable standard.
7. **Over pressure effect:** ±0.03% URL.
8. **Dynamic performance:** The dynamic response of the transmitter is dependent on HART and Fieldbus systems, and each has its own response time. HART and Fieldbus have been discussed in Subsection 2.1.2.3 above.

TABLE XI/2.3.2-1 Static Pressure Effect (values of A is defined within the table)

Sensor Type	Zero Error		Span Error	
	Pressure < A	Pressure > A	Pressure < A	Pressure > A
Type X	0.05% URL/bar (P < 2 bar)	±0.05% URL/bar (P > 2 bar)	±0.05% Span/bar (P < 2 bar)	±0.05% Span/bar (P > 2 bar)
Type Y	±0.1% URL for 0 < 100 bar	±0.1% URL/100 bar for P > 100 bar	0.1% span for P < 100 bar	±0.1% span/100 bar for P > 100 bar

Data given in Section 2.3.0 have been taken from ABB, Emerson, and Yokogawa.

2.4.0 Specification

Nowadays transmitters are available with highly accurate ability to communicates over a long distance with the help of digital communication means. Added to this, the application area of transmitters has been widened also. Therefore, it is important to know how to specify process transmitters. This section briefly discusses the specifications of DPTs and MVTs. Though not specifically mentioned here because not all transmitters suffer from performance variations due to mounting position, some transmitters do suffer from performance degradation for mounting position.

2.4.1 SPECIFICATION OF DIFFERENTIAL PRESSURE TRANSMITTERS

A brief specification of a DPT has been given in Table XI/2.4.1-1.

TABLE XI/2.4.1-1 Specification of Differential Pressure Transmitter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Sensor technology	Manufacturer standard out of various technologies discussed in Section 4.1.1 of Chapter III		Subsection 4.1.1.4 of Chapter III
	Material specification			
2	Isolating diaphragm	SS 316, Hastelloy C276, Monel, etc.		Refer to Section 2.2.1 above
3	Sensor and wetted parts	SS 316, Alloy 276, Monel, etc.		DO
4	Housing	Cast aluminum		Refer to Section 2.2.2 above
5	Cover/flange/process connector	ASTM CF- 8M		DO
6	Filling fluid	Silicone oil/inert fluid		DO
7	Min/max span and range	Application-dependent* Span ratio at specified accuracy may be lower		
8	Zero/span adjustment (may not be applicable for flow measurement)	0%−100% min		
9	Process connection	¼ or ½″ NPT or G ½ or flange type especially for remote seals		
10	Electrical connection	¼ or ½″ NPT or G ½ M20 X 1		
11	Output	4−20 mA HART/BRAIN protocol		
12	Fieldbus	Profibus/Foundation		Commonly used FB
	Performance specification			
13	Accuracy	±0.055% FSD*		Refer to Section 2.3.1 above
14	Repeatability	±0.052% FSD		
15	Stability	±0.005%/(>)5 years		

Continued

TABLE XI/2.4.1-1 Specification of Differential Pressure Transmitter—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
16	Power supply effect	±0.005%/V		
17	Response time*	90 ms (dead time ~40 ms) Typical for HART fieldbus these will be different. Refer to Subsection 2.1.2.3		Dead time included
18	Ambient temperature	−20°C to 70°C		
19	Power supply (load*)	24 VDC (10.5−40 VDC)		*Load varies with supply Refer to Section 2.1.2 above
20	SIL Certification	IEC61508: SIL- 2/3		
21	Self-diagnostic	CPU/Hw failure		Hw: Hardwire
22	Certification	Hazardous services		
23	Display and OP interface	LCD display intelligent		OP: Operator
24	Operator interface			
25	Mounting	2″ horizontal/vertical pipe		
26	Accessories	Valve manifold, mounting bracket, bolts, etc.		

2.4.2 SPECIFICATION OF MULTIVARIABLE TRANSMITTERS

As indicated during our previous discussions in Section 2.1.4, in MVTs in a single sensor, both DP and absolute (or gage) pressure are measured and associated flow computer mass flow is calculated with the help of the transmitter signal along with the external temperature sensor, as shown in Fig. XI/2.4.0-1. Here it can be seen the transmitter has two tappings similar to DPT, and there is one external temperature probe mounted in the pipeline and electrically connected through

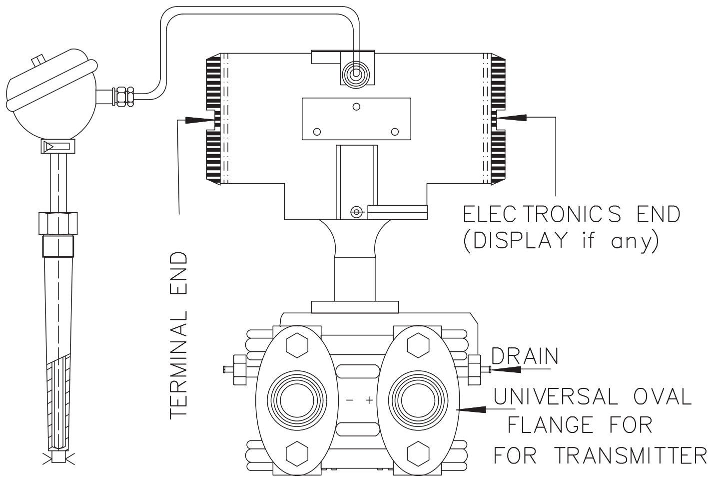


FIGURE XI/2.4.0-1 Multivariable transmitter.

an external cable. In the figure the output cable is taken from the other side of the transmitter not shown in the diagram.

The basic theoretical parts discussed for DPTs are also applicable for MVTs, hence they are not repeated here, instead we look into the specification. Multivariable transmitters are specified in Table XI/2.4.2-1.

2.5.0 Mounting and Installation of DPTs and MVTs

Mounting: Basically there is no difference in mounting of pressure transmitters and differential pressure transmitters, as well as multivariable transmitters. Therefore, Fig. III/4.2.1-1 is applicable here. Only in the case of mounting in

TABLE XI/2.4.2-1 Specification for Multivariable Transmitter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Sensor technology	Manufacturer standard out of various technologies discussed in Section 4.1.1 of Chapter III Temperature sensor: RTD Pt100		Subsection 4.1.1.4 of Chapter III
	Material specification			
2	Isolating diaphragm	SS 316, Hastelloy C276, Monel, etc.		Refer Section 2.2.1 above
3	Sensor and wetted parts	SS 316, Alloy 276		DO
4	Housing	Cast aluminum		Refer to Section 2.2.2 above
5	Cover/flange/process connector	ASTM CF- 8M		DO
6	Filling fluid	Silicone oil/inert fluid		DO
7	Min/max span and range	DP range: 1–5000 mbar in different ranges and span Static pressure range* 20/250 bar Temperature: −200 to 850°C		*gage/absolute
8	Zero/span adjustment (may not be applicable for flow measurement)	0%–100% min		
9	Process connection	¼ or ½″ NPT or G ½		
10	Electrical connection	¼ or ½″ NPT or G ½ M20X1 Two sets: one for output and the other for temperature input		
11	Output	4–20 mA HART protocol		
12	Fieldbus	Profibus/Foundation		Commonly used FB
	Performance specification			
13	Accuracy	DP: ±0.15% FSD standard or better Static pressure: ±0.22% or better Temperature ±0.5 Ambient temperature: nearly ±0.1 or better Mass flow nearly 1% for 10:1 flow rate span		Refer to Section 2.3.1 above

Continued

TABLE XI/2.4.2-1 Specification for Multivariable Transmitter—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
14	Repeatability	±0.052% FSD		
15	Stability	0.005%/(>)5 years		
16	Power supply effect	±0.005%/V		
17	Response time*	DP: 200 ms HART Static pressure: 200 ms HART Fieldbus: 300 ms for both		*Dead time included
18	Ambient temperature	−20 to 70°C		
19	Power supply (load*)	24 VDC (10.5−40 VDC)		*Load varies with supply Refer to Section 2.1.2 above
20	SIL certification	IEC61508: SIL- 2/3		
21	Self-diagnostic	CPU/Hw failure		Hw: Hardwire
22	Certification	Hazardous services		
23	Display and OP interface	LCD display intelligent		OP: Operator
24	Operator interface			
25	Mounting (some may have mounting position effect)	2″ horizontal/vertical pipe		
26	Accessories	Valve, manifold, mounting bracket, bolts, etc.		
27	Basic flow	Mass flow, standard volume flow for gas and liquid, and volume flow for gas		
28	Auto compensation mode	Configuration of the fluid physical properties and primary element		

transmitter enclosure provision shall be kept for impulse line layout for both legs for MVT and DPT in place of single limb for pressure transmitter shown. In the case of MVT, additional cable from the temperature probe should be taken care of. So far as the external temperature probe (RTD) of MVT is concerned it is to be mounted in the pipeline (preferably in the downstream side of the element). In the case of DPTs or MVTs with integral orifice/Pitot tube/average Pitot (Annubar), the transmitters need to be at the field and to be mounted in the way already discussed in Chapter II for the applicable flow element type.

Installation: Basically, the installation of DPT and/or MVT involves installation of impulse lines from flow elements. Typical installations of impulse lines pertinent to orifice, flow nozzle, and Venturi elements have already been covered in Chapter II. Similar installations would be applicable also for Pitot tube, V cone, etc. Impulse line installations have been shown separately for transmitters below and above the source point. These are shown for DPTs and are equally applicable for MVTs. Table XI/2.5.0-1 may be referenced for installation details for DPTs and MVTs for transmitters both above and below the source point.

TABLE XI/2.5.0-1 Installation Drawing Reference for Both DPT and MVT

Flow Element Type	Transmitter Below Source	Transmitter Above Source
Orifice plate	Fig. II/2.2.4-1	Fig. II/2.2.4-2
Flow nozzle	Fig. II/3.2.4-1	Fig. II/3.2.4-2
Venturi	Fig. II/4.2.3-2	Fig. II/4.2.3-1

The discussions for process transmitters are now concluded and we now describe another device often used in flow measurement, such as dosing, i.e., the metering pump.

3.0.0 METERING PUMP

All metering pumps are positive-displacement pumps. These are a special category of pump often used in instrumentation control for precise flow metering and dosing control. In many controls such dosing controls are used as final control elements in the control loop. They also find their use in chemical reagents and in chromatographs. Of the positive displacement pumps, those used as metering pumps *have no, or only very little, internal and/or external leakage* and *can provide the precision and accuracy that are normally required of a metering pump* [4]. Metering pumps find their applications in precise adding or charging of difficult fluids like slurries, molten metal, liquefied gases, corrosive, radioactive, toxic, flammable materials, chemical dosing materials, etc. They are used for measured precise discharges with the ability to vary capacity manually or automatically as per process conditions and process control demand. In some cases the capacity variations can be in proportional mode with respect to some other parameter. Metering pumps can handle a wide range of chemicals, including acids, bases, corrosives, or viscous liquids and slurries or otherwise difficult fluids such as, melts or liquid metals, and radioactive, toxic, and flammable materials. A high level of repetitive accuracy is an important feature for metering pumps. Metering pumps can be categorized as peristaltic pumps and piston pumps. Piston (piston-assisted) pumps are of two types, one is a mechanical piston or plunger pump with a gland and the other is a diaphragm or bellow type without a gland. There is another category of glandless pump known as a pulsator pump. The speed or stroke of the metering pump is controlled to precisely control the feed. Such stroke control can be achieved by an actuator or by speed control of the drive, which can be an electrical or hydraulic type.

3.1.0 Peristaltic Metering Pumps

The most common and well-known peristaltic movement is found in the human body in involuntary movements of the longitudinal and circular muscles in the digestive tract. Similar contracting and relaxing movement is utilized in pumping technology.

3.1.1 WORKING PRINCIPLES AND TYPES OF PERISTALTIC PUMP

Peristalsis is characterized by alternate contraction and relaxation, to push the fluid from the inlet to the outlet of a hose/tube. Such movement is different from normal pump operations. Thus, in a peristaltic pump, the fluid is moved forward through a flexible container, e.g., a hose/tube, by progressively contracting or squeezing from the inlet side to the outlet or discharge side. The flexible container referred to above should be made from materials with resilience, to allow it to recover to its original shape immediately when relaxed after contraction.

A variety of methods are deployed for squeezing the tube (or container) to produce flow, including the following.

- Rollers that are connected to a rotating body squeeze the tubing against a circular housing, as shown in Fig. XI/3.1.0-1 (type 1).
- Rotating wobbling cam squeezes a tube against a hose/tube, as shown in Fig. XI/3.1.0-1 (type 2).

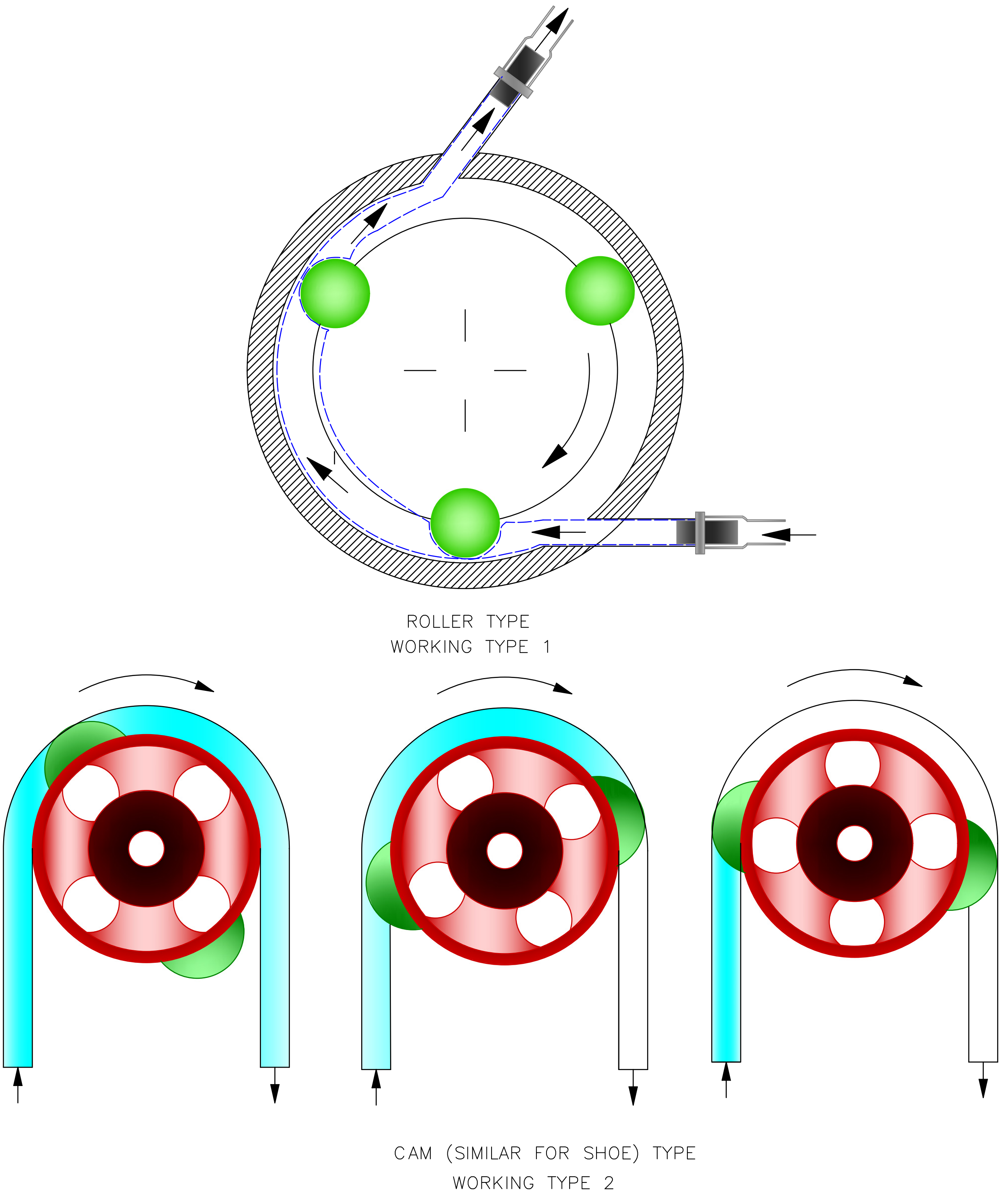


FIGURE XI/3.1.0-1 Peristaltic metering pump types.

Cam-operated fingers successively squeeze the tubing against a flat surface. Rollers that are driven by a chain drive squeeze tubes against a flat plate [4].

- Some use a rotor and shoe to press the hose/tube and will have a vacuum to pull fluid to enter the hose/tube.

From the figures it is clear that the hose/tube is the major component of the pump that comes into contact with the fluid. Normally plastic materials are mostly used. Although plastic materials are very suitable for corrosive fluids, pressure and temperature pose limitations on its use in the process. These are used for low-flow applications. The peristaltic pump finds wide applications in medical and biochemical fields, mainly characterized by hygienic and sterilized uses coupled with high accuracy and low-flow rates. Also, peristaltic pumps find applications in industrial and domestic uses, such as in swimming pools and food and beverage industries. Peristaltic pumps can be categorized into high-pressure and low-pressure pumps. In the next section the characteristic features of these are elaborated.

3.1.2 CHARACTERISTIC FEATURES OF PUMP CATEGORIES AND SPECIFICATION

In this section, categories of pumps, along with various parameters needed for specification are discussed.

1. **Categories of peristaltic pump:** Broadly, peristaltic pumps can be categorized as high-pressure and low-pressure pumps. Their characteristic features are described here.
   - *High-pressure pump:* High-pressure peristaltic hose pumps capable of handling pressure up to 15 barg deploy a hard shoe type design, as the roller type design is mainly meant for low-pressure service. In high-pressure hose pumps, reinforced tubes with high thickness are used and have casings filled with lubricant to prevent any damage to the hose due to abrasion [5]. These pumps require much more energy to operate than low-pressure roller pumps for same flow delivery.
   - *Low-pressure pump:* Low-pressure peristaltic pumps use rollers for their operation in squeezing the tube. As these tubes are not reinforced lubrication may not be necessary, hence they have dry casting. There are mainly two types of roller: spring-operated rollers and fixed occlusion rollers.
2. **Specification:** Normally peristaltic pumps are specified by furnishing data to include but not limited to the various parameters listed below:
   - Tube size;
   - Connection type;
   - Number of rollers;
   - Number of channels;
   - Flow capacity;
   - Feed rate;
   - Pressure-handling capability;
   - Power supply;
   - Motor spec;
   - Speed control;
   - Others, such as solid content (slurry), lubrication;
   - Accessories;
   - Options (if any).

   We now look into the part details along with the technical parameters for peristaltic pumps. Here the highest possible values have been specified.

3.1.3 PARTS AND TECHNICAL DETAILS OF PERISTALTIC METERING PUMPS

The following are the major components in peristaltic pumps. Also, the associated technical details for these pump have been elaborated on.

1. **Major components:** The major components of peristaltic metering pumps include but are not limited to the following:
   - Pump case;
   - Hose;
   - Rotor;
   - Shoe;
   - Motor;
   - Drive control.

In peristaltic metering pumps the flow rate can be varied by changing the speed of the squeezing mechanism. Common AC/DC motors have a supply voltage of 240 VAC 50 Hz or 110 VAC 60 Hz, or 220 VDC.

2. **Technical details:** There are various sizes of pumps and hoses available. The following technical details may be noted for high-pressure high-flow peristaltic metering pumps. Recently, some manufacturers of a specialized type of peristaltic pump, the progressive cavity pump, have been providing versions that are optimized for metering pump use [4]. Peristaltic metering pumps have the capability to handle highly viscous fluids, like sludge, and slurries, such as chocolate, tomato paste, etc.

   High-capacity peristaltic metering pump details have been listed below (e.g., Peristaltic Pump DULCO flex).
   - *Connection sizes up to:* from DN 25 to DN 100;
   - *Feed rate:* 20 L/rev;
   - *Flow capacity:* 14,400 L/h;
   - *Max pressure:* 15 barg;
   - *Hose material:* NR, NBR, EPDM.

3.1.4 APPLICATION AREAS FOR PERISTALTIC METERING PUMPS

In addition to extensive use of peristaltic pumps in the medical field, they also find applications in industrial areas also, such as those listed here:

- Chlorine disinfection, flocculation in swimming pools;
- *Water treatment:* Metering pumps are used for feeding chemical additives into the water. These are used in water treatment plants in, e.g., energy-generation plants;
- Chemical processing and reactor feed;
- Handling of viscous fluids, such as tomato ketchup in food and beverage industries;
- Laboratory dispensing.

3.2.0 Piston-Operated (With/Without Diaphragm) Metering Pumps

As stated earlier there are basically two kinds of piston- or plunger-operated metering pump. One is the direct plunger or piston operated on without any diaphragm and the other is with a diaphragm. In the former case the plunger/piston is directly in the chamber and is in contact with the fluid. In the diaphragm-operated one the plunger operates the diaphragm, which is in contact with the fluid. In general a piston pump essentially consists of the following basic components/systems and characteristics; these are applicable to all types of piston pumps with or without a diaphragm.

1. **Driver:** Normally the pump is driven by one AC drive with constant speed and the stroke of the piston is controlled to regulate the flow. However, speed controls are often used nowadays. Pneumatic or hydraulic drives are also used.
2. **Driving mechanism:** It is the driving mechanism which converts the rotating motion into reciprocating motion. Worm gear crank shafts are normally deployed. These are kept in an oil bath for cooling purposes.
3. **Flow adjuster:** The pump flow rate is adjustable by adjusted by varying the stroke length or speed of revolution, i.e., stroke speed. In many cases this is done using adjustable micrometers.
4. **Liquid end:** This refers to the part of the pump in contact with the fluid. Therefore, the material of construction is determined by the service condition, temperature, and type of fluid to be handled. Normally check valves are used and for leakage control check valves in series are often deployed. Packing materials, especially where fluid comes in contact, plays an extremely crucial role. Naturally proper selection is very important.
5. **Pump characteristics:** This is a positive displacement pump. Unlike the centrifugal

pump it has linear characteristics, i.e., flow and pressure are not in a linear relationship (there), but are linear (here), in fact pressure essentially is constant over the flow range. The flow versus stroke characteristic curve is linear, but does not pass though the zero stroke point because up to a certain stroke there will not be any flow, it needs piston push to pressurize the system. Therefore, it is a straight line cutting the x axis in flow versus stroke characteristic graph. A steady accuracy of ±1% or better is available from piston type metering pumps. Also, flow versus speed (of drive) is linear and similar flow versus stroke characteristics.

The description and part details given are generalized in nature to get an overall idea about the pump which is basically a mechanical item, but process and instrumentation engineers need to know the basics of it, as they are often used for measurement and control. With this basic idea the discussions start with the direct piston type metering pump.

3.2.1 DESCRIPTION OF A DIRECT PISTON-OPERATED METERING PUMP (NO DIAPHRAGM)

As the name suggests the mechanical piston pump piston or plunger undergoes a reciprocating motion within a chamber, as shown in Fig. XI/3.2.0-1. A major plus point for direct piston design includes high suction and discharge pressure capabilities; high temperature resistance, and the *lowest NPSH* requirements [6]. On account of this reciprocating motion a fixed volume of fluid is delivered in each stroke. This somewhat resembles positive displacement meter, the only difference is the in PD meters, based on flow quantity, the fixed-volume rate discharge is decided, whereas in a metering pump for desired flow, the fixed-volume discharge is regulated. For this reason this is called a positive displacement pump.

This fixed-volume flow rate is dictated by the area of the piston covering the fluid, so, the flow rate is a function of three factors: area of piston, length of the chamber, and speed of piston stroke. The displacement volume of the pump is the area of the plunger multiplied by the stroke length. Direct piston pumps are available for high discharge flow as well as high pressure. With a smaller plunger area, the same energy flow will be available at higher pressure. This is theoretical volume discharge. There are two options for direct piston type pumps: piston pumps with or without a valve.

1. **Piston pump with a valve:** In a piston pump with a valve the actual volume discharged will be less than the theoretical volume. This is because there will be some of the fluid returning into the chamber during the closing period of the check valves. Also, there may be some leakage. Direct piston design is not recommended to be used for toxic or hazardous fluids. To reduce leakage through the check valve, in many cases check valves are placed in series. As seen in Fig. XI/3.2.0-1 one can see that there are two check valves—one at the inlet/suction end and one at the discharge or outlet end. During reciprocating motion, when it is withdrawn from the chamber, there will be less pressure in the chamber, which will cause check valves (balls) to move towards the chamber. Due to disposition of the ball check valves, the inlet port will be open, allowing fluid to enter the chamber and at the same time the discharge/outlet port will be closed by the ball check. On the other hand, the reverse will happen when the piston moves in towards the chamber, i.e., the discharge end will be opened, whereas the other end will be closed. From the above discussions it is clear that there will be pressurization in one direction. Hence there will be pulsating flow. In order to eliminate the pulsating nature of flow, the following methods may be implemented:
   - Use a dampening chamber (like putting capacitance such as low-pass filter, in electrical circuit), i.e., an accumulator; or

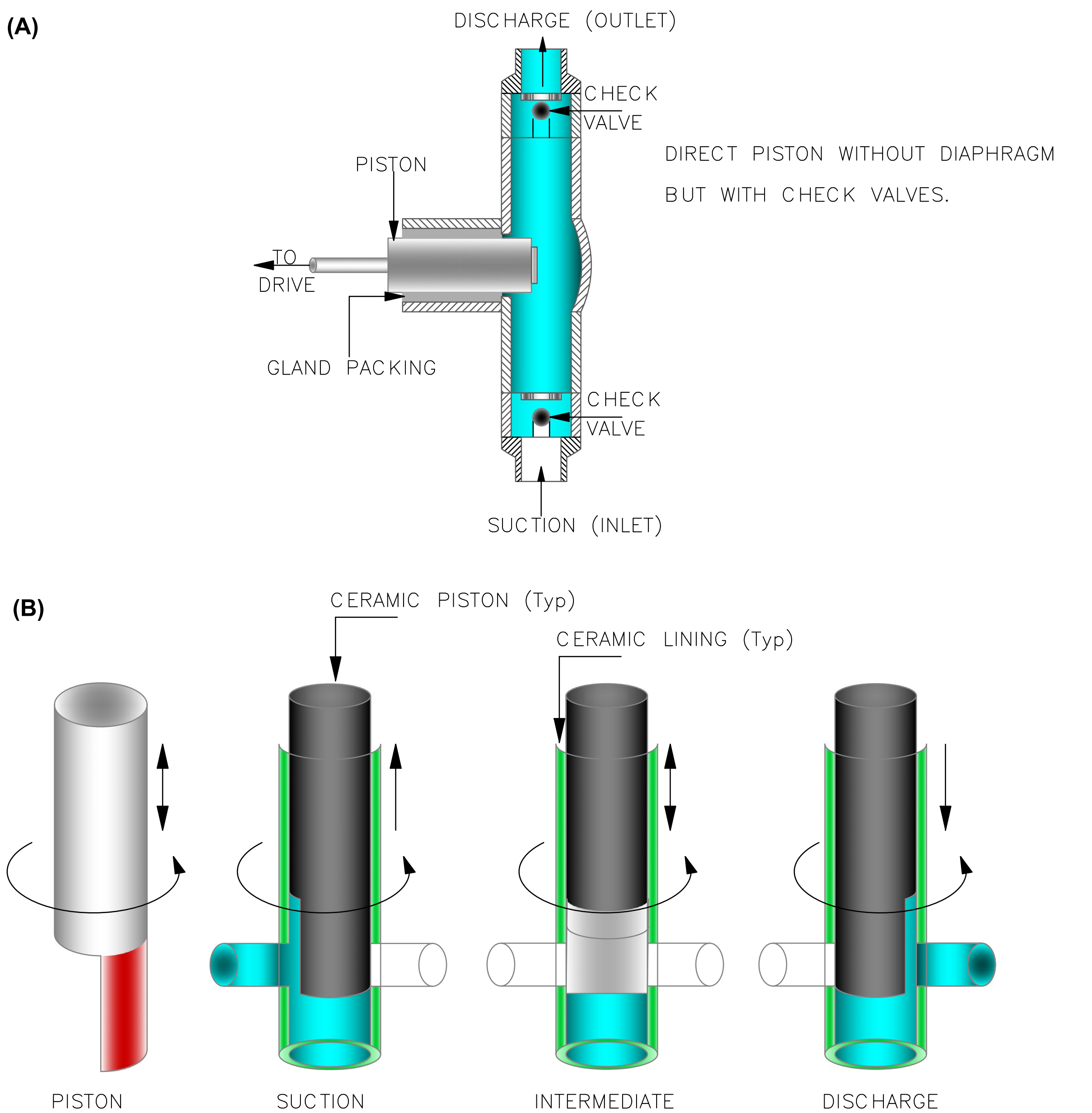


FIGURE XI/3.2.0-1 Plunger/piston metering pump. (A) Plunger/piston metering pump with valves. (B) Valveless plunger/piston metering pump. *This has been developed based on an idea from Fluid Metering Pump Operation, Fluid Metering Inc. (Valveless metering pumps and dispensers; Catalog). http://fluidmetering.com/meteringPump-Animation.html. Courtesy: Fluid Metering Inc.*

- Use a number of chambers/pistons in combination in parallel (somewhat similar to a Variable resistance trim—VRT valve!) and accordingly these are named as duplex (two), triplex (three).

As indicated in the initial discussions, the plunger and many other parts come directly into contact with fluid, and so, it is extremely important that there is proper selection for materials of construction for the various

components of a piston pump. Worn valves and fluid compressibility at high discharge pressures further reduce the volumetric efficiency (usually around 95%) of plunger pumps [4]. Referring to Fig. XI/3.2.0-1A it can be seen there is packing with the piston. It is extremely important to select appropriate packing material.

2. **Piston pump without a valve:** There is another version of the direct piston pump where there is no valve (check valve). In this design, as shown in Fig. XI/3.2.0-1B, the piston is made up of ceramic material and has a special design as shown in the left-most figure in Fig. XI/3.2.0-1B. At the lower part the cylindrical piston is cut, which is due to its rotation and gives a passage for the inlet to flow through the inlet port and discharge fluid from the outlet port as shown in the three positions of the piston in Fig. XI/3.2.0-1B. This means that there are two motions of the piston, one is a linear reciprocating motion at the same time as rotational motion. As shown during suction, the piston rotates with the cut portion facing the inlet port, allowing fluid to get in and accumulate below the piston. During the intermediate portion (both in suction and discharge motions) both ports are covered by the piston. During the discharge part the outlet port gets connected with the fluid in the chamber. Thus it is seen that the requirement of the check valve to isolate the inlet from the outlet, i.e., for fixed volume determination, is met by the rotation of the piston with a special cut as seen in the metering pump from Fluid Metering Inc. [7]. The flow capacity can be easily adjusted by adjusting the length of the piston. It is possible to calibrate using the front knob. This pump can also be used to measure and control reverse flow easily. However, these are available in limited sizes of up to 15 mm.

We now look at the various components and materials of construction (MOC) for these.

3.2.2 DIRECT PISTON METERING PUMP COMPONENTS AND THEIR MATERIALS OF CONSTRUCTION

Piston pumps have a number of materials that come into contact with the fluid, which could be abrasive materials, slurries, etc. Therefore the selection of materials is extremely important. When metering abrasive slurries, such as kaolin, diatomaceous earth, and metal-based catalysts, it is necessary to introduce a clean flushing fluid [4]. The major components of these and their common materials of construction (MOC) are listed below. This is only for guidance and depending on the actual application some other material may be suitable, therefore it is recommended that the manufacturer be consulted.

1. **Piston material:** Ceramic/316SS/304 some use stainless steel with PTFE lining.
2. **Cylinder case:** Fluorocarbon (EPDV)/316SS/Tefzel (for valveless pump).
3. **Liner:** Ceramic, carbon (for valveless pump).
4. **Metering valve:** SS304, SS316, and ceramic.
5. **Ball valve:** Silicon dioxide, SS304, SS316, silicon compound, and ceramic.
6. **Gland packing:** The plunger packing must be carefully selected, not only to minimize leakage and wear but also for lubrication, cooling, sterilization, and flushing [4]. PTFE is normally selected as the packing material.
7. **Other components:** As mentioned earlier, other components include the driver, motor (explosion-proof as applicable), driving mechanism, and lubrication system.

3.2.3 TECHNICAL DATA

Generally, the metering pump type is specified on the basis of the following parameters.

1. **Maximum/minimum discharge rate:** Liters/hour;
2. **Pressure:** Bar;
3. Operating temperature of fluid in degrees Celsius;
4. Motor power in kW;

5. **Type of fluid:** Fluid properties including abrasiveness;
6. **Meter flushing:** if required;
7. **MOC of component:** with special requirements;
8. **Standard compliance:** API standard.

3.2.4 MAJOR APPLICATION AREAS

The following are major application areas of direct piston type metering pumps:

1. Waste water treatment;
2. Environment protection;
3. Oil and gas industries, including exploration;
4. Power generation;
5. Paper industries;
6. Pharmaceutical industries;
7. Food and beverage industries;
8. Military applications;
9. Automatic dispensing machines.

We now close the discussions on direct piston type pumps to see how diaphragm type pumps operate and give some details about them.

3.2.5 GENERAL DISCUSSIONS ON DIAPHRAGM PUMPS

The piston pump with a diaphragm is often referred to as a simple *diaphragm pump*. This is essentially a piston pump, only, instead of direct contact of the piston with the fluid, a diaphragm is used in between. The diaphragm-operated pump uses a flexible member to transmit a pulsating force to the pumped fluid without allowing external leakage, e.g., packing to come in contact with the fluid. This force transmission is similar to what is experienced in a diaphragm-operated pressure sensor. In the process fluid side, it uses inlet/suction and outlet/discharge check valves to direct and regulate the flow. Let us see some of the features for diaphragm- and piston-operated metering pumps. However, drive and driving systems have been described separately:

1. **Diaphragm:** The diaphragm acts as a barrier between the piston and fluid. The diaphragm can be metallic or nonmetallic. Metallic diaphragms are hard, whereas nonmetallic materials such as Teflon, neoprene, or a similar material are soft in nature. As the diaphragm pump is a sealed one it is recommended for hazardous and toxic fluids.
   - *Metallic diaphragms:* These give very good performance in high-pressure/high-temperature applications, with very critical environmental conditions, and with variations in process parameters. They find their applications in oil and gas areas, including in oil exploration. For longevity and durability, a metallic diaphragm is preferred.
   - *Nonmetallic diaphragm:* Nonmetallic diaphragms are available in wide varieties of materials, such as polypropylene, PVDF (Kynar), groundable acetal, Santoprene, medical grade Santoprene, PTFE (Teflon) w/Santoprene backer, neoprene, EPR, viton. These are very suitable to handle highly corrosive fluids. Normally they show greater flexibility.

   There are two options for diaphragm movements: a direct piston and through hydraulic oil.
2. **Piston:** Diaphragm movement directly by reciprocating motion of the piston is shown in Fig. XI/3.2.0-2A. In this method, instead of a diaphragm, a bellow may be used. In this type of design normally the piston size is greater when compared with that for an hydraulically operated diaphragm pump. The material of construction of the piston will be similar to what has been discussed above. However, as the piston does not come in contact with fluid there will be less restriction on material selection.
3. **Hydraulic operation:** In this type of design there is no direct contact of the piston with the diaphragm. The reciprocating piston pumps the hydraulic oil, which in turn delivers the forces to the diaphragm to operate. Therefore, the hydraulic oil force replaces the direct mechanical forces on the diaphragm. This type of design has been depicted in Fig. XI/3.2.0-2B. As shown, in the

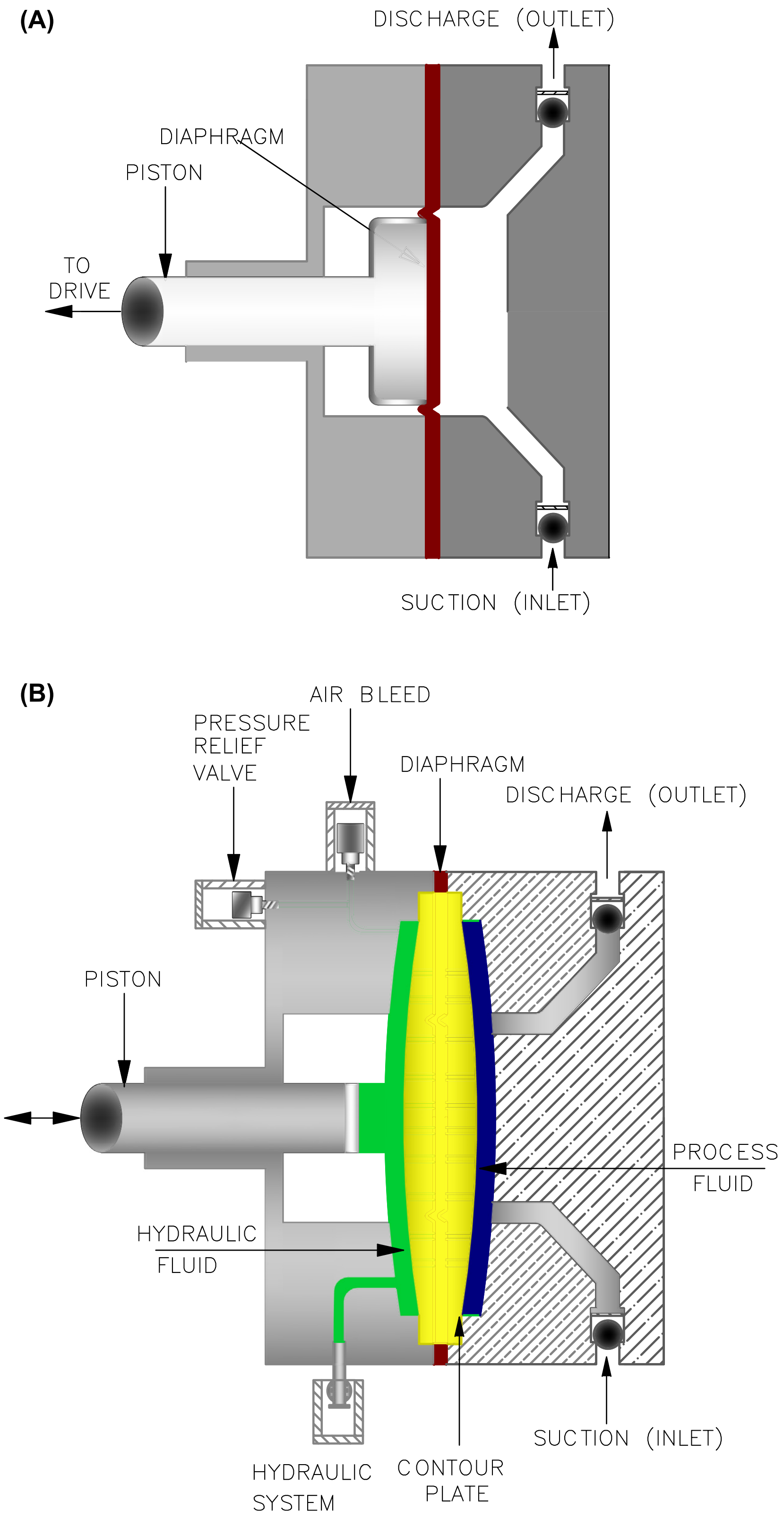


FIGURE XI/3.2.0-2 Diaphragm-operated metering pump. (A) Piston-driven diaphragm pump. (B) Hydraulic-driven diaphragm pump. *Developed based on Fluid Metering Pump Operation, Fluid Metering Inc. (Valveless metering pumps and dispensers; Catalog).* http://fluidmetering.com/meteringPump-Animation.html. *Courtesy: Milton Roy.*

diaphragm there are fluids in both sides. One side is hydraulic oil and the other side is process fluid. Therefore the hydraulic type diaphragm pump is inherently balanced as pressures at the two sides balance each other and this helps in eliminating diaphragm stress. There are two contour plates as support to keep the diaphragm deflections well within the limit of endurance and increase the life span of the diaphragm. As shown in Fig. XI/3.2.0-2B, the hydraulic and process fluids pass through carefully engineered holes in the contour plates in order to come into contact with the diaphragm [6]. This type is not suitable for slurry applications as it has to pass through small holes in the diaphragm contour.

4. **Other devices for hydraulic operation:** There are three other valve systems used for refilling the system: the hydraulic system, pressure relief valve, and air bleed system.
   - *Hydraulic system:* The hydraulically operated diaphragm system requires one hydraulic oil system. This system is responsible for refilling the system to compensate for hydraulic fluid lost during normal operation on account of bleeding past the piston or through an air bleed valve or hydraulic fluid pushed out through the relief valve in the case of high pressure. The hydraulic system replenishes such losses. In modern hydraulic systems the refill valve does not need any adjustments. Also, in these high-performance diaphragm designs there is no possibility of hydraulic fluid overfilling, hence there is no need to perform delicate procedures to synchronize hydraulic fluid balances [6].
   - *Pressure relief valve:* There will be one external safety valve to protect the piping from overpressure. However, hydraulic diaphragm pumps normally have internal safety valves to protect the pump also. Additional external safety valves are also recommended for piping. These are available in PVC and SS 316.
   - *Automatic air relief valve:* In order to bleed entrapped air automatic air bleed valves are part of the hydraulic system design.
5. **Miscellaneous accessories for diaphragm pumps:** There are a number of other devices used in connection with diaphragm pump, these are listed here:
   - *Backpressure valve:* In order to prevent from free-flowing fluid passing through the valve, a backpressure valve is necessary so that it can help to develop greater pressure in the discharge line. The discharge line always requires higher pressure than that in the suction line. When it is not possible for the process to supply a set pressure above the suction line, then backpressure valves assist the pressure. These are available in PVC and SS316 [6].
   - *Pulsation dampener:* As stated earlier, due to the reciprocating motion of the pump, there will be a pulsating nature to the discharge flow. Normal process demands most of the pulsation be diminished. Therefore, a pulsation dampener is required. This is a kind of accumulator. Dampeners are available for pressures up to nearly 100 barg. Sizing is based on cubic inch/stroke displacement of the specific pump [6].
   - *Other accessories:* There are a few other accessories used with diaphragm pumps, namely, calibration columns, mixers, chemical feed tanks, etc.
6. **Cost factor:** Since in hydraulic piston operated diaphragm pump, complete hydraulic system along with various valves are needed the cost of the same will be higher when compared with direct piston type.
7. **Power handling:** A direct piston-operated diaphragm pump can handle low pressure and low flow of process fluid, when compared to same handling capability with its hydraulic counterpart, because excess direct force from the piston may damage the diaphragm.
8. **Other design aspects of the diaphragm system:** As in the case of pressure sensing, here also the bellow design can handle a

vacuum and can withstand higher temperatures. The glandless metering pumps can handle toxic, corrosive, radioactive, high-purity, odorous, volatile, and abrasive materials [4].

We now look into the details of the diaphragm pump.

3.2.6 DRIVE AND DRIVE MECHANISM OF DIAPHRAGM PUMPS

Be it direct piston operation of the diaphragm meter or hydraulic type diaphragm, an electric motor (AC/DC) is used. Between the motor and piston there will be a gear mechanism to convert the rotational motion into reciprocating motion, as well as for speed reduction. The piston is driven by crank shaft arrangements.

1. **Stroke length adjustment:** Worm gear arrangements are deployed. Worm gear arrangements are used for getting variable stroke length adjustments. These are immersed in the lubricating system to reduce the temperature and smooth out the operation. Normal worm gear arrangements of 10:1 turndown are achievable as at lower speed they lose the oil shield [6]. Some manufacturer, such as Milton Roy, have developed helical gear set operating with low noise and low friction. Here also the entire arrangement is submerged in oil. This arrangement, according to the manufacturer's claim, can provide 100:1 TD with high steady state accuracy and repeatability [6].
2. **Variable speed:** Apart from stroke length control, feed control can be accomplished by varying the speed of the driver, i.e., the motor. This can be applied to the system by keeping a driving mechanism similar to that described above. Mostly variable drives are deployed with AC/DC motors and can achieve TD of about 35:1. Major control issues crop up at lower speed, for which TD cannot be made high. However, there are brushless DC motors with advanced controllers available, which can give good results at low speeds too. These systems can offer speed controls with an accuracy of ±0.1% and can be utilized for turndown of 100:1. Centrac of Milton Roy is an example of the same. For drive/motor speed control section 4.6.0 of chapter VIII may be referenced.

3.2.7 PERFORMANCE DATA FOR DIAPHRAGM PUMPS

The performance data for diaphragm pumps are as described here:

1. **Turndown:** Possible turndown: 100:1;
2. **Overall accuracy:** Steady-state overall accuracy: ±0 5% FSD or better;
3. **Speed control accuracy:** 0.1% FSD or better;
4. **Capacity:** 2−4200 L/h;
5. **Pressure:** up to 150 barg;
6. **Set point adjustment:** Manual micrometer and/or electronic process signal;
7. **Actuator types:** electrical/pneumatic;
8. **Electronic process control signal:** electronic signal to electrical and/or electro-pneumatic positioner 4−20 mADC;
9. **Pneumatic process control signal:** 0.2−1.0 kg/cm^2 (through I/P converter);
10. **Position accuracy:** 0.5% FSD.

It is worth noting that these data are given from reputed manufacturer's data and the best possible parameters have been shown. Naturally all these requirements may not be met by a single instrument. Application of this type of metering pump is similar to that described for direct piston pumps, and hence is not repeated here. So we now have a look into a practical control loop from energy generation application.

There are some other types of metering pumps, including solenoid valves. Now we look into a practical example of metering pump applications.

3.3.0 Metering Pump in Dosing Control (Application Example)

Fig. XI/3.3.0-1 shows a typical control loop normally encountered in power plants for regulating the pH of feed water. Based on the condensate flow quantity of ammonia dosing in the condensate at BFP suction is done. For this

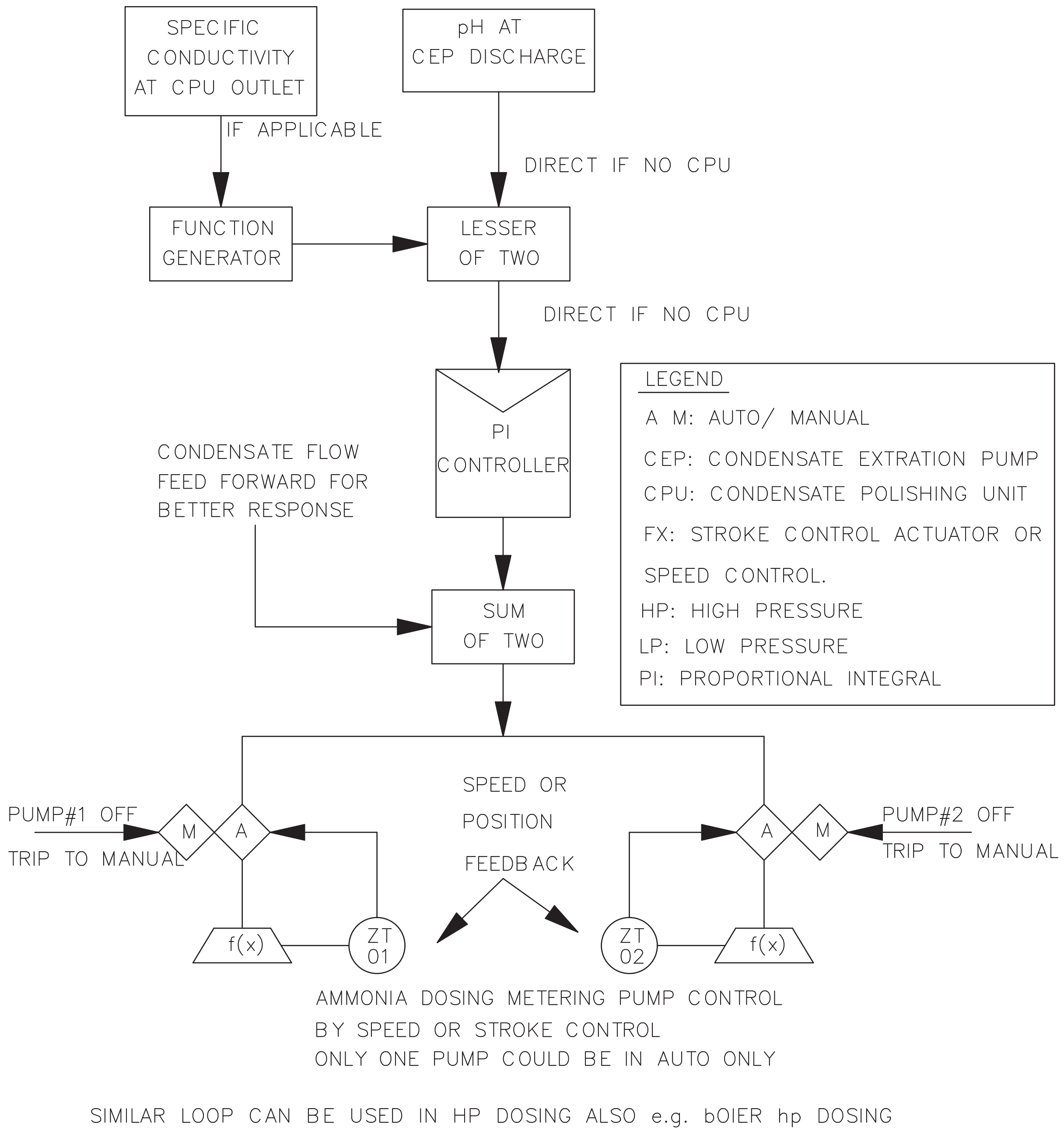


FIGURE XI/3.3.0-1 Metering pump for LP dosing. *For further details on dosing system, S. Basu, A. Kumar, Debnath, Power Plant Instrumentation and Control Handbook, Elsevier, November 2014. http://store.elsevier.com/Power-Plant-Instrumentation-and-Control-Handbook/Swapan-Basu/isbn-9780128011737/ may be referenced.*

the pH value at the condensate extraction pump (CEP), which is the main condensate pump, discharge is measured and acts as a measured value, which is compared with the desired set point. As seen in the figure, if there is a condensate polishing unit (CPU) for the utility station, then specific conductivity at the CPU outlet could also be taken as measured value. A minimum

selection is used to get the minimum value between CPU outlet conductivity and pH at the CEP discharge. PI controllers are used to regulate the stroke of the metering pump meant for dosing. In the drawing there are two dosing metering pumps, normally one is in operation. Both pump controls can be manual, but only one can be automatic. An example has been given for low-pressure dosing control. In high-pressure applications, boiler dosing pumps are also deployed for phosphate dosing. These have been discussed in detail in Chapter V of Ref. [8]. Interested readers may refer to the author's book [8].

3.4.0 Double Diaphragm Mechanically Actuated Diaphragm Metering Pump

We know that the diaphragm which comes directly into contact with process fluid is referred to as a primary diaphragm. From the point of view of the slightest leakage or fluid coming into contact with packaging, it is recommended that for corrosive fluids it is better to use an hydraulically operated diaphragm so that process fluid is isolated by the barrier fluid, i.e., hydraulic oil. Now the following question does come to mind, "in the latter case will there be any leakage of barrier/hydraulic fluid to process fluid?" This possibility may be remote but cannot be ignored. If it happens in a pharmaceutical plant for a batch, then the entire batch may have to be rejected. For this some manufacturers have a double-diaphragm mechanically actuated diaphragm. In the case of dangerous or corrosive fluid pumping, it is recommended that there should be an additional secondary/backup diaphragm for isolation. Some manufacturers incorporate a double-diaphragm construction, similar to an hydraulically actuated metering pump but without any hydraulic oil in between, i.e., it contains no fluids, only a secondary piston. This means no fluids can be pumped into the product. Also in some design use pressure switch set at the lowest level, to detect the leakage.

With this the discussions on metering pumps are concluded and we now investigate the energy flow calculator, which is also an important aspect of flow metering.

4.0.0 ENERGY FLOW COMPUTATION AND METERING

In modern material world energy is probably the scarcest element. Added to this, there is the threat from global warming and pollution to mankind. Naturally all industries are trying to find various ways and means to develop their systems as energy efficiently as possible. In order to make the systems energy efficient it is necessary to measure their energy efficiency. This means that both input as well as output energy flow at each and every stage has to be measured and accounted for. Flow metering plays a critical role in monitoring the energy flows, both in the existing system as well as after any energy-efficient effort has been undertaken, i.e., to measure and/or compute the energy flow pattern both before and after the optimization of the process. Extremely reliable measurements data are absolutely necessary for designing any energy-efficient system to minimize pollution due to heating as well as gas emissions, etc. Also, no accurate cost−benefit analysis can be made without reliable measurement systems. The payback period for the installation is determined by dividing the optimization costs with the measured yearly energy saving [4]. In this section brief discussions are presented on energy flow computation. Not only is energy efficiency of systems important, but it is also important to know the quality of steam and fuel frequently used as the source of energy, i.e., the enthalpy of steam or the heat value of fuel. In this section, discussions also cover the measurement of enthalpy of steam or heat value of fuel. However, it should be borne in mind that in this section emphasis is placed on flow metering mainly. Therefore, the discussions can be divided into two parts, i.e., finding energy flow for a heat exchanger and quality aspects of various media

used in heat exchangers. This concept has been clarified in Fig. XI/4.0.0-1.

Another issue important here is that in order to calculate the quality of heat exchanging media, (e.g., for calculations of heat value for fuel), it would be necessary to use calorimetric sensors/ or Wobbe index sensors, which are beyond the scope of this book. However, one should note that standard Wobbe index instruments are available (namely, Hobre instruments).

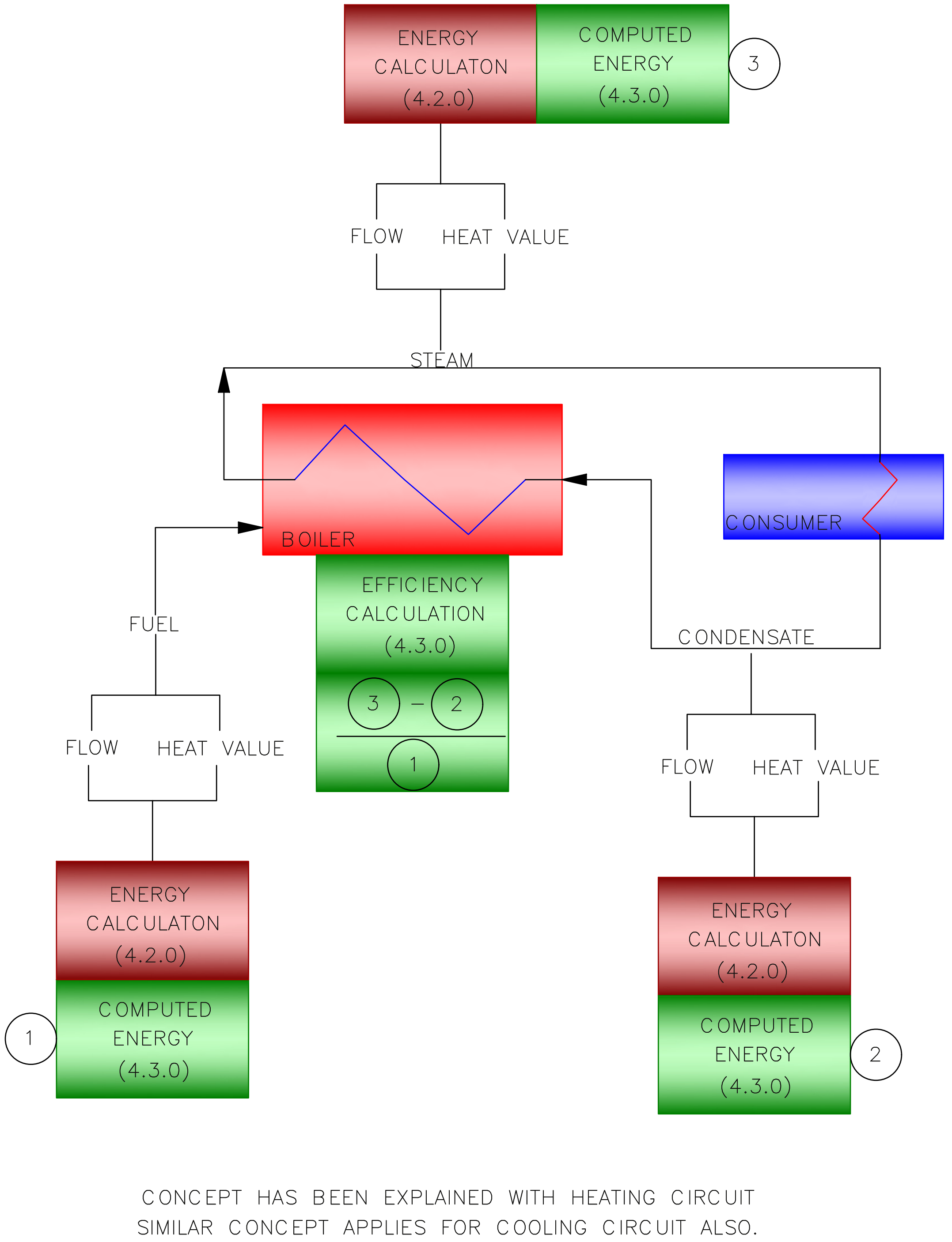


FIGURE XI/4.0.0-1 Energy flow measurement concept.

However, the basic Wobbe index has been explained in Fig. XI/4.2.0-1. Interested readers may consult any standard instrumentation book for the same. We begin the discussion with a general discussion of the concept followed by energy flow through steam, chilling water, and/or fuel, i.e., finding energy in steam, chilling water, and fuel flows. Based on the calculated energy in each of these flow lines the efficiencies of various heat exchangers are evaluated in the next section. A brief concept of class I and II calculations of boiler/thermal power plants is included. For further details on thermal power plant efficiency calculation, the author's Chapter VII of the Power Plant Instrumentation and Control Handbook [8] may be referenced.

4.1.0 General Discussions on Energy Flow and Its Requirements

In-process and/or mechanical system energy flows from one system to another and even if the concerned system is working fine there can be variations in performance. Here generalized discussions have been presented for commonly used heat exchanging systems such as boiler HVAC, etc. to present an idea of the same. Specific discussions have been presented in subsequent sections. Let us take as an example a boiler system, even if the mechanical system functions perfectly there may be deviation in performance from the design values, a major reason for this may be attributed to variation in fuel property and calorific value. Similarly, in HVAC systems there can be variation in performance due to chiller water quality. Therefore, energy flow at each of the stages may be extremely important. If there is leakage in the air heater in a boiler the boiler efficiency drops, even there is no fuel property variation. Therefore, in process systems it is necessary to monitor the flow and quality of the following nonelectrical utilities:

- Chilled water;
- Hot water;
- Condenser water;
- Steam;
- Fuel, e.g., natural gas;
- Compressed air.

Two major cases of such applications include boiler energy flow monitoring as well as in HVAC systems. In small boilers and heat generators, energy flow/BTU meters can be applied. However, in the case of utility boilers simple energy flow/BTU meters do not find many applications on account of their complexity. In the case of a utility boiler there are various subsystems, such as air flow and heating, fuel flow and heating (HFO system), there will be some heat loss with flue gas discharge at the induced fan (ID fan), or may be some loss through air heater leakage. In steam system there may be losses through various subsystems, e.g., loss due to blow down. It is quite a complex system and is guided by various standards like ASME PTC 4.1 (Steam generating units performance test code), ASME PTC 4.4 (Gas turbine heat recovery steam generators performance test code), and DIN 1942 (Acceptance Test for Steam Generators). Brief discussions on boiler efficiency have been covered in Section 4.3.0. Within the limited scope of this section elaborate discussion on the same is not possible, however interested readers may refer to Chapter VII of the latest version of the Power Plant Instrumentation and Control Handbook [8].

HVAC is another good example where energy flow meters or BTU meters are used. Let us take a simple example of a chiller unit as shown in Fig. XI/4.1.0-1A, where the coefficient of performance of the chiller can be measured by the ratio of the energy flows between the output and input of the chiller unit. So, in a similar manner, the efficiency of the individual heat exchangers can also detected by monitoring the energy flows on both the utility and the process sides of the exchanger. Based on this, the system can be extended to a building as shown in Fig. XI/4.1.0-1B. In this building if there are n number of floors (assuming each floor has one consumer), for proper monitoring of energy flow, the same for each consumer

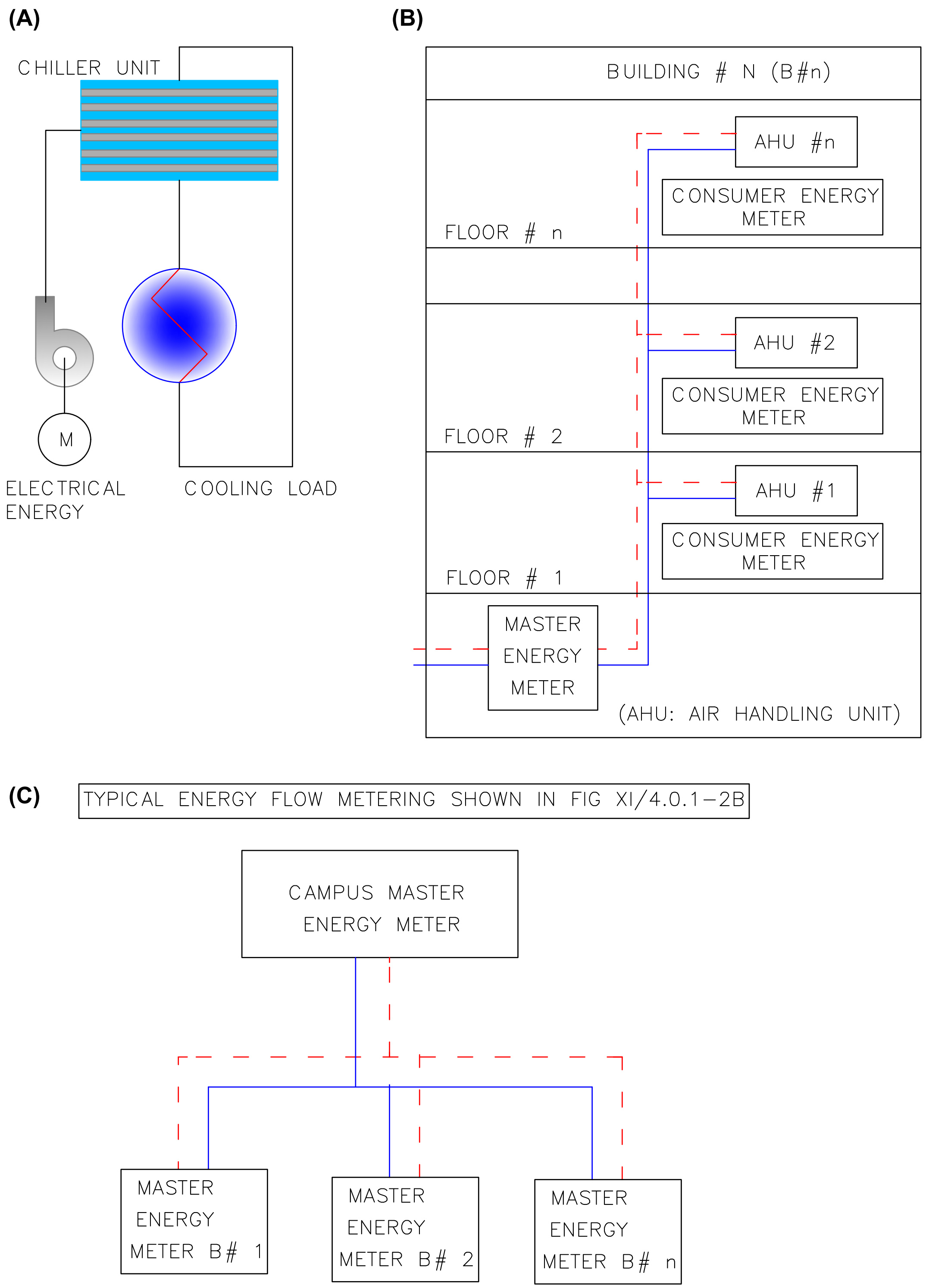


FIGURE XI/4.1.0-1 HVAC energy flow in building and campus. (A) HVAC concept. (B) HVAC in building. (C) HVAC in a campus.

needs to be monitored. This can be extended for a campus comprising various buildings, as shown in Fig. XI/4.1.0-1C.

In the case of the campus the main source of the HVAC system has also been shown. This is not meant for industrial use. A central AC plant for industrial use is shown in Fig. XI/4.1.0-2A. Fig. XI/4.1.0-2B shows the essential elements for an energy flow meter or BTU meter. For a simple heat exchanger, one needs to at least note the temperature difference between the inlet and outlet across the heat exchanger for the utility fluid and quantity of utility fluid.

In such a case it is assumed that there is no loss in the system, however in an actual case his may not be correct. For this reason measurement of the temperature difference of process fluid as well as quantity of flow of the same needs to be addressed. In the case of industrial applications there may be a central cooling tower to take care of the main chillers which have been shown and normally are provided in redundant mode. Chilling water supply headers are normally formed for making supply to the different plant-specific chilling units with the help of redundant fans and a common chilling return line. There is a common bypass line to regulate flow in the system.

Now we take another look at the issue of heat transfer. Suppose for any process there is a requirement for a hot water supply. Normally process water is passed through a heat exchanger

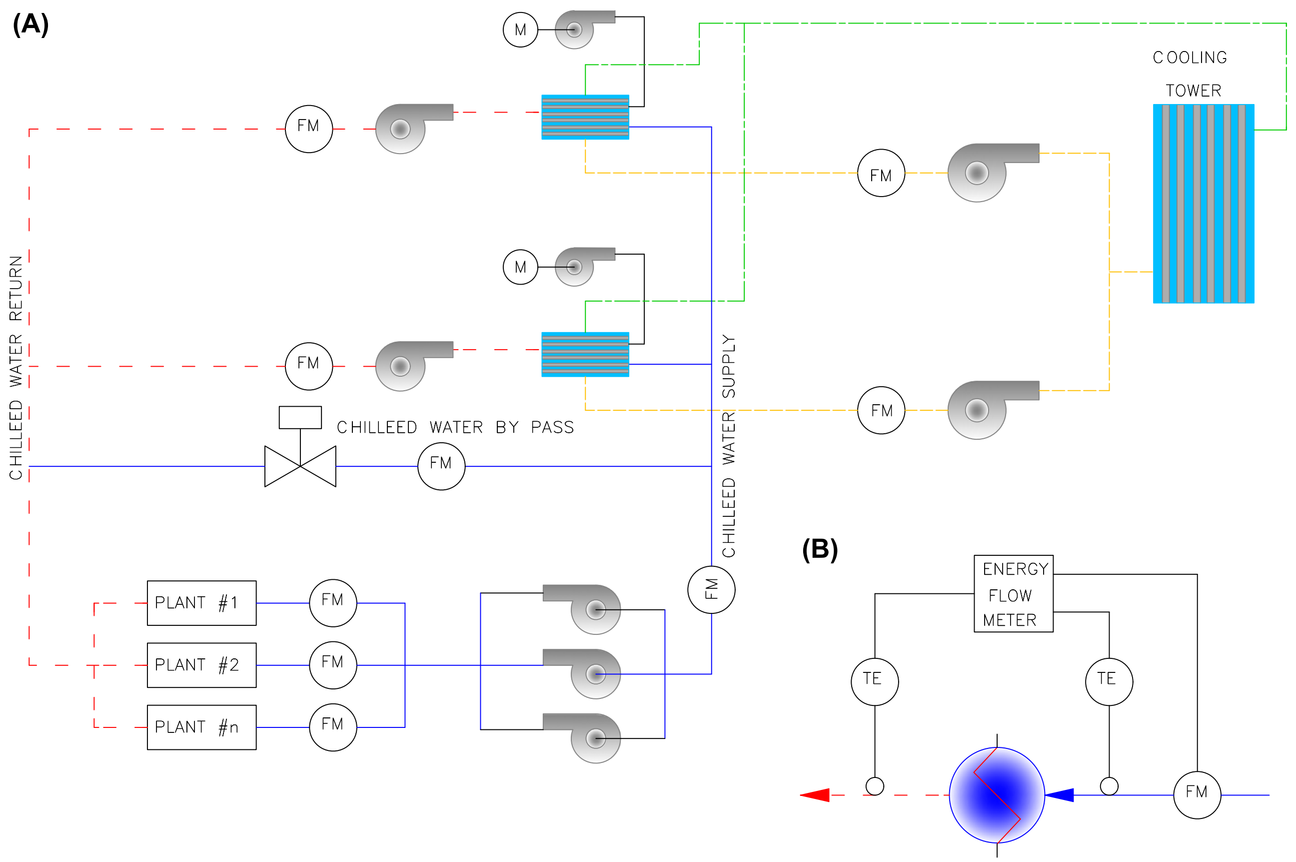


FIGURE XI/4.1.0-2 Industrial HVAC energy flow meter. (A) Plant HVAC energy flow scheme. (B) Typical energy flow metering scheme.

which is being heated by, e.g., steam and the inlet and outlet temperature of the process water is measured. If the incoming process temperature is low or if the flow process water increases then more steam is sent. The reverse is done in the case of higher temperature and lower flow of process water. Is it possible to maintain the outlet temperature of process water in this way? Yes, theoretically this may be possible, but the system becomes very slowly responsive. Most readers probably understand why I said "may be" and "slowly responsive." This is because if there are no wide variations in steam quality, it is possible, but it could be a slower response, because if steam flow and quality are not taken care of, then on account of the inherent slow response of temperature the loop will be slowly responsive. On the other hand, if there are drastic changes in the steam quality the said control loop may not function at all. If the steam is supplied from a steam pressure- and temperature-reducing station (reducing steam from 100 barg at 540°C to say 16 barg at 210°C) and temperature control loop for the reducing station fails. In such a case steam at very high temperature will be coming to the heat exchanger and on account of huge variation of the steam ***quality*** it may not be possible to control the process water temperature. Similarly, as stated earlier, theoretically if all the conditions of the boiler remain unchanged, put simply, if the fuel properties and/or heat value changes, there will be a drastic change in boiler performance. All these have been discussed to indicate that the quality of fuel and steam also affect energy flow in the system. There have been efforts to monitor the energy flow of fuel and steam by energy flow/BTU meter. According to B.G. Liptak in Ref. [4] "The heat flow rate provided by the burning of a fuel gas can be measured by detecting its mass flow rate and multiplying it by its heating value, which can be detected by Wobbe index sensors or calorimeters." This means that for fuels like natural gas/oils/coal, etc. one needs to measure the calorific value, in addition to measuring the flow. In the next section short discussions will be presented on the use of energy flow metering in finding the quality of steam/fuel.

4.2.0 Energy Metering for Fuel and Steam

When one recalls the basic calorimetry one finds that the heat flow rate value can be obtained by multiplying mass flow of fuel with the associated heating value of the fuel. The Wobbe index gives the indicative heat value. In this section the discussion will be on fuel gases as well as the quality of steam and these are related to combustion control, and so short discussions on these will also be covered. However, before we move on to other issues we address some of the technical definitions.

4.2.1 IMPORTANT TERMS FOR FUEL GAS IN COMBUSTION

Listed below are a few technical terms which are very important in understanding fuel gas in combustion.

1. **Heating value/calorific valve (CV):** The amount of heat evolved by the complete combustion of a unit volume of fuel (gas) in air.
2. **Specific gravity of gas:** This represents the ratio of density fuel gas and density of air.
3. **Wobbe index:** The Wobbe index (WI) is the main indicator of the interchangeability of fuel gases and is frequently defined in the specifications of gas supply and transport utilities. The Wobbe index is used to compare the combustion energy output with different compositions of fuel gases. If two fuels have identical Wobbe indices then for given pressure and valve settings the energy output will also be identical. The Wobbe index is a critical factor to minimize the impact of fluctuations in fuel gas supply and can therefore be used to increase the efficiency of burner or gas turbine applications. For the definition and mathematical expression of Wobbe index Fig. XI/4.2.0-1 may be referred to.

WOBBE INDEX (WI): Wobbe Indices are critical for gaseous fuel supply and distribution. Two fuels with identical Wobbe indices will give same energy output under given pressure and valve settings. Wobbe index is very important in sorting out fluctuations of gas supply.

Wobbe index is defined as ratio heating value of gas and square root of specific gravity

i.e. **Wobbe Index** = $\frac{\textit{Heating value}}{\sqrt{\textit{specific gravity}}}$

FIGURE XI/4.2.0-1 Wobbe index.

4. **Combustion air requirement index (CARI):** This is another important term normally encountered in natural gas combustion. It should not be confused with the stoichiometric ratio. CARI indicates the required amount of dry air to burn 1 Nm^3 of fuel gas compensated for the specific gravity of the gas. The mathematical expression of CARI is very similar to the WI.

$$\text{CARI} = \frac{\text{Air demand}}{\sqrt{\text{specific gravity}}}$$

5. **Discussions on WI and CARI:** The two terms WI and CARI are not related to each other, but are somewhat connected with each other through the combustion control loop. CARI provides the information on the air fuel ratio and is essential in calculating efficient combustion and minimizing emissions. On the other hand, WI actually regulates the energy flow in a combustion system, through feedback controls.

4.2.2 USE OF WI FOR HEAT FLOW

From the previous discussions it has been noted that for measurement of energy flow it is often necessary to know the calorific value of fuel. The energy (heat) flow rate (Q) of a fuel can be calculated as the product of its mass flow rate with the calorific value (CV). So for a known gas at standard conditions, the volumetric flow (q) and CV can be used to get the heat flow. Variations in composition affect both the heating value of the fuel gas and the pressure drop produced when the gas passes through any restriction, i.e., the orifice plate. The volumetric flow through an orifice plate (q) can be expressed as the product of a constant (k) and the square root of the ratio of Δp/SG, where Δp is the pressure drop across the flow element. Therefore, for the heat flow rate Q for head type flow measurement using Bernoulli's equation (Chapter II) one can write:

$$\text{Energy flow } Q = q \cdot CV = k\sqrt{\frac{\Delta p}{SG}} \cdot CV \tag{XI/4.2.2-1}$$

or by rearranging the equation and replacing 1/k with K one can write:

$$\sqrt{\Delta p} = q \cdot \sqrt{SG} \cdot \frac{1}{k} = K \cdot q \cdot \sqrt{SG} \tag{XI/4.2.2-2}$$

By definition (Fig. XI/4.2.0-1) WI $= \frac{CV}{\sqrt{SG}}$, so one gets

$$WI \cdot \sqrt{\Delta p} = K \cdot q \cdot \sqrt{SG} \cdot \frac{CV}{\sqrt{SG}} = K \cdot Q \tag{XI/4.2.2-3}$$

Hence Q is proportional to WI. Nowadays, the Wobbe index can be measured continuously in hazardous areas, this approach provides an online method of detecting heat flow rate [4].

Thus WI can be measured with a WI instrument and this value can be utilized for measurement of energy flow measuring. Heat values of some commonly used fuels have been listed in Table XI/4.2.0-1.

TABLE XI/4.2.0-1 Heat Value of Commonly Available Fuels

Fuel	Types	Major Constituents[a]	Heat Value Range
Natural gas	1 through 4	CH_4, C_2H_6, C_3H_8, H_2S, CO_2	$31–42 \times 10^6$ J/m^3
Refinery gas	1 through 3	CH_4, C_2H_6, C_3H_8, N_2, CO_2	$18–69 \times 10^6$ J/m^3
Coke oven gas		CO, H_2, Other HC, N_2, CO_2	21×10^6 J/m^3
Blast furnace gas		CO, H_2, N_2, CO_2	3×10^6 J/m^3
Fuel oil	3 (2,4,6)	C, H, N, O, S and ash	$40–45 \times 10^6$ J/kg
Kerosene		C, H, N, O, S	46×10^6 J/kg

[a]*All constituents not included.*

4.2.3 ENERGY FLOW COMPUTATION IN GAS AND STEAM

Gas and steam energy computing instruments can be used for the following calculations:

Energy (steam) flow: The heat quantity is calculated based on enthalpy and mass flow(-for steam).
Energy flow for gas: Energy flow calculation is based on WI and material flow.
Energy balance: Based on mass balance in upstream and downstream pipe, an energy balance
Closed systems: Tailored for closed "steam to condensate" systems.
Net energy computation: Accurately calculates net energy by accounting for energy in returning condensate.
Steam energy flow: Energy flow = Mass flow × Specific enthalpy.

4.2.4 FUEL ENERGY FLOW METERING AND COMBUSTION CONTROL

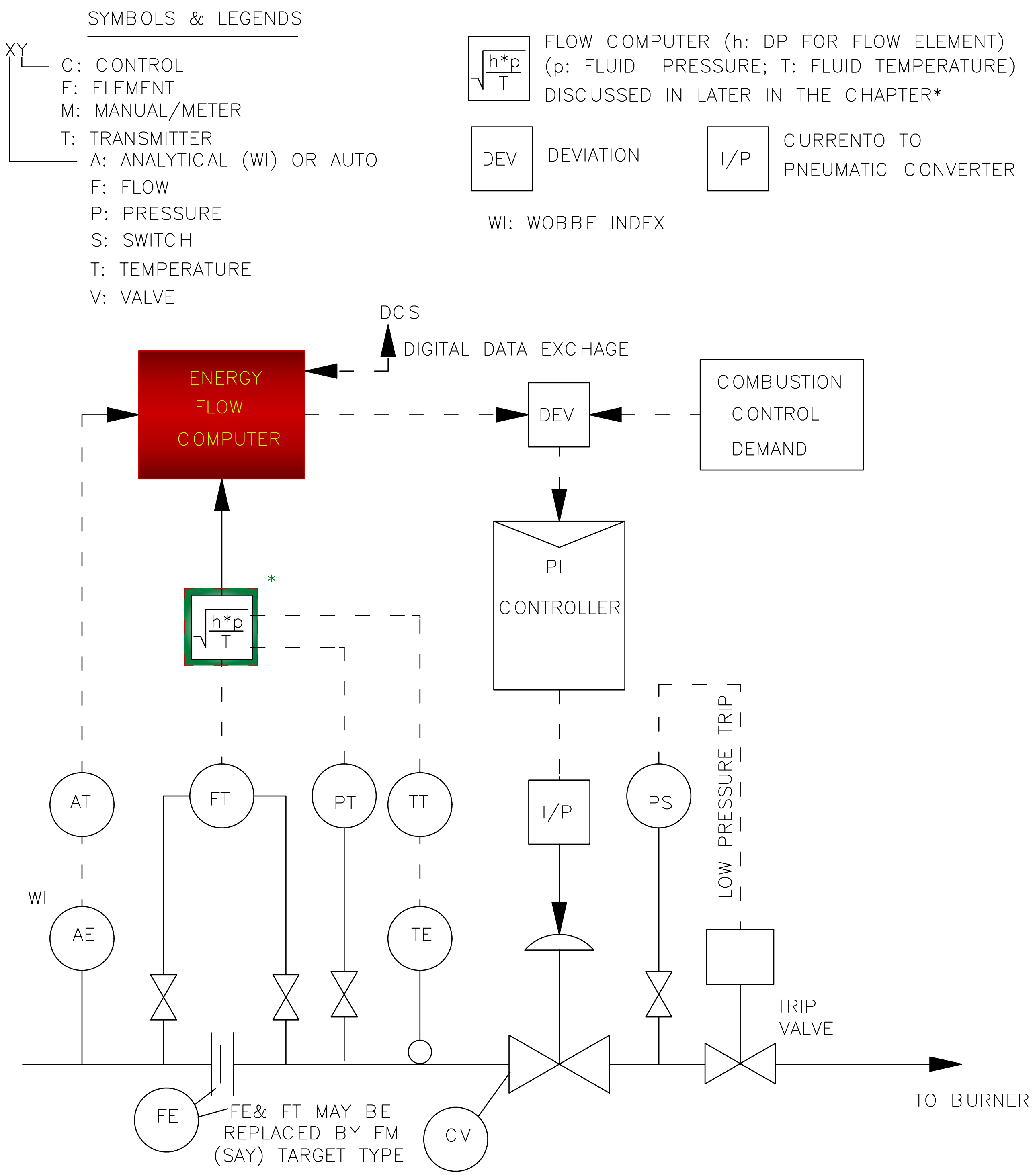
We now see how energy flow/BTU meter can be applied in a control loop pertinent to a combustion control loop. A typical fuel control loop has been depicted in Fig. XI/4.2.0-2. In this loop typical fuel gas flow is measured with pressure and temperature compensation to compute mass flow in a flow computer. The fuel calorific value is measured by WI instruments and taken to the energy flow/BTU meter along with the gas flow measured at standard conditions. The output of the energy flow meter is compared with the fuel demand from combustion control to regulate the fuel gas control valve to regulate fuel gas to the burner.

As shown in the figure, a low-pressure trip has been kept in the system so that minimum header pressure is maintained at the fuel gas header to ensure flow through the burner. From the energy flow/BTU meter, numbers of outputs are available in hardware form as well as digital communication type. We now have brief discussions on energy meters.

4.2.5 ENERGY FLOW/BTU METER DISCUSSIONS AND SPECIFICATION

Basically, an energy flow meter is a flow computation unit, as already discussed in Section 8.2.0 of Chapter I. During the discussions therein, a detailed description including the types of flow meters used have been discussed. Therefore, this part should be read in conjunction with Section 8.2.0 of Chapter I. In this section a brief specification of the meter is given. Normally there are a number of parameters available from the energy flow meter, some them include but are not limited to the following:

1. **Parameters for gas application:** The following parameter displays and outputs are available.
   - Corrected volume flow;
   - Pressure/temperature;



TYPICAL APPLICATION OF ENERGY FLOW METER SHOWN FOR LOOP. HERE FLOW COMPUTER* DISCUSSED LATER ARE SHOWN SEPARATELY. IN RELAITY IT MAY BE PART OF ENERGY FLOW METER. LOW PRESSURE INTERLOCK SHOWN JUST TO COMPLETE THE LOOP.

FIGURE XI/4.2.0-2 Energy flow meter in control loop.

- Mass flow;
- Calorific value;
- Specific gravity.

2. **Parameters for steam application:** The following parameter displays and outputs are available.
   - Corrected volume flow;
   - Mass flow;
   - Energy;
   - Process temperature;
   - Process pressure;
   - Specific weight;
   - Enthalpy.
3. **Specification of energy flow/BTU meter:** A brief specification of the meter has been given in Table XI/4.2.0-2.

   With this the discussion on energy flow/BTU meters for fuel and steam quality measurements comes to an end and we now look into how these meters can be utilized for efficiency computations.

4.3.0 Energy Flow or BTU Meter Application for Heat Exchanger Efficiency

As stated earlier, the energy flow/BTU meter is basically a type of flow computer (see Section 5.0.0). The energy flow/BTU meter is applied in measuring fuel and steam quality measurement. Similarly, it can be extended for measuring the efficiency of various heat-exchanging equipment and systems, such as boilers (especially small and medium-sized process boilers) and HVAC. In this section brief discussions on this application to boilers shall be looked into, as its application for HVAC has already been covered in Section 4.1.0.

4.3.1 BOILER EFFICIENCY CALCULATION WITH ENERGY COMPUTATION UNIT

Recalling the discussions presented in Section 4.1.0 of this chapter, we now see how the energy computation unit can be utilized in computing

TABLE XI/4.2.0-2 Specification of Energy Flow/BTU Meter

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Display	Backlit LCD display 2–4 lines 6–15 mm height		
2	Keyboard	Dedicated sealed membrane type		
3	Power supply	240/110 VAC 50/60 Hz		
4	Transmitter supply	Yes, three		
5	Ambient temperature	−20 to 55°C		
6	Humidity	95% RH (condensing)		
7	Enclosure	IP65		
8	Nonvolatile memory with retention period > 20 years	For setup, totals, and logs		
9	Battery	Lithium type for 5 years life		
10	Battery health	2–3 indication		
11	Input	Universal quantity: manufacturer's standard, logic input		

Continued

TABLE XI/4.2.0-2 Specification of Energy Flow/BTU Meter—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
12	Output (HW)	Pulse, digital (potential free contact relay output), 4–20 mADC		
13	Communication	Links with standard protocol: RS 485/232 with parity checks Fieldbus and networking possible (part of flow computer)		
14	Fieldbus	Possible		
15	Programmable	Algorithm for ideal gas, natural gas, saturated/ superheated steam		
16	Built in table	Specific gravity, enthalpy		
17	HVAC capability	Heating, cooling, and conditioning		
18	Data logging	Storage of energy totals by hour, day, week, or month		
19	Modes of operation	Heating mode, heating–cooling, and charge –discharge mode		
20	Calculation	Density, enthalpy, energy, peak energy, and efficiency in addition to sum, difference square root		
21	Accuracy	±0.1% AR or better		
22	Resolution	8 Bit (min)—as per manufacturer standards		

boiler efficiencies. Some of the units available can carry out optimization functions also and recommend the mode of operation of the boiler. In such computations it has to acquire data from the boiler and a few manual data, e.g., specific gravity for the fuel or steam table, etc. to be inputted into the device. The device may be a compact one located at the control environment or it may consist of a field unit and computational unit with displays for mounting in the control environment. Both units may be connected using a two-wire cable for transferring data using a suitable link and protocol, e.g., MODBUS or even using fieldbus as per the manufacturer standard. The main computation unit located in the controlled environment possesses an operator interface with displays and keyboard, programming facility, and manual intervention by authorized personnel, as typically shown in Fig. XI/4.3.0-1.

These units are available from almost all major reputed instrumentation companies. Most of them provide both hardwired output in 4–20 mADC, pulse, contact outputs, as well as digital links and protocol for communicating the unit with DCS, and other secondary instruments such as video graphic recorder, indicator, etc. Some use embedded systems and microcontrollers (as mentioned in Section 8.2.0 of Chapter I) and support fieldbus communication as shown in Fig. XI/4.3.0-1. Let us now look into the basics of the calculation.

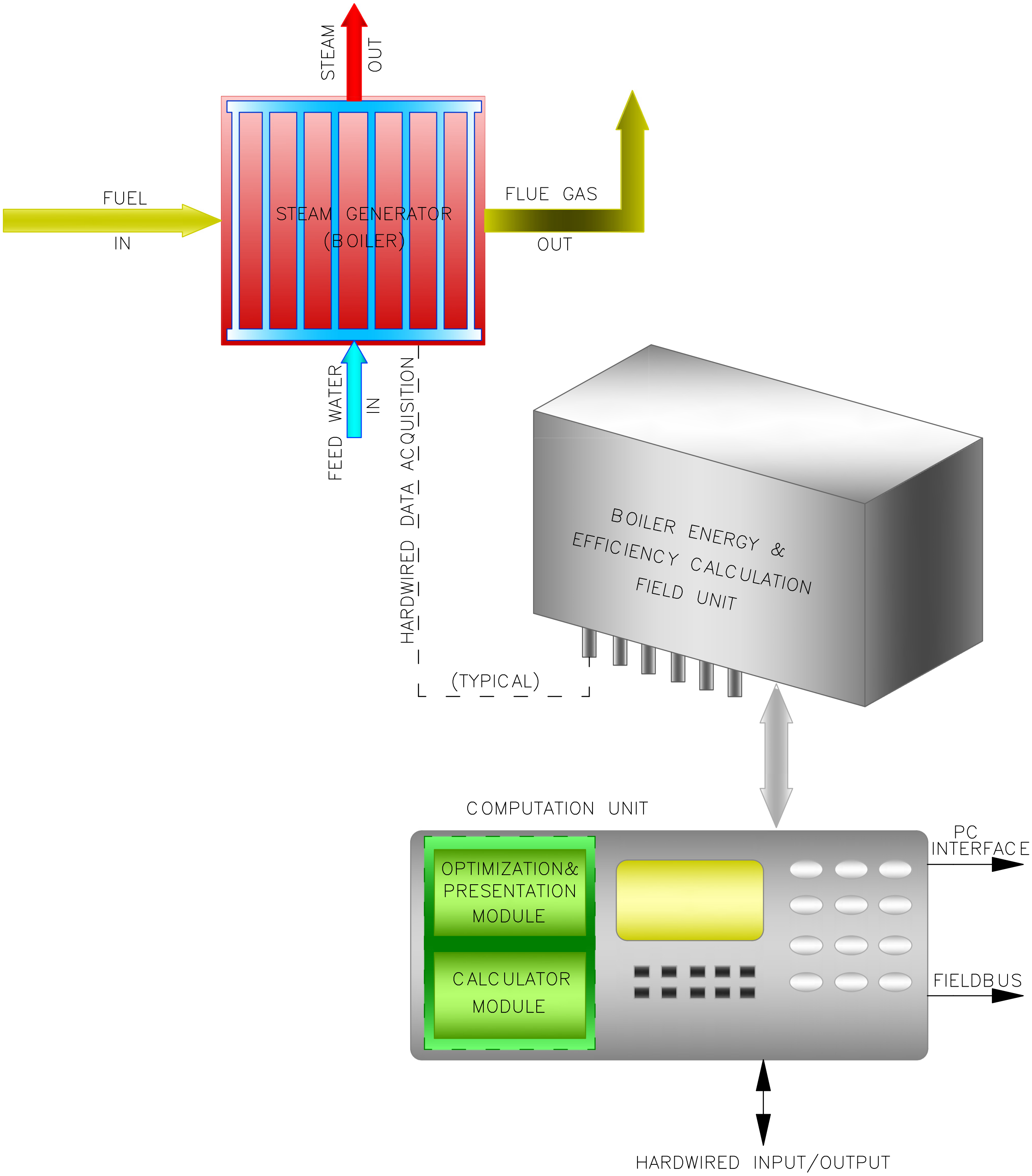


FIGURE XI/4.3.0-1 Boiler efficiency computation.

4.3.2 BOILER EFFICIENCY FORMULATION AND MEASUREMENT POINTS

1. **Simplest efficiency formulation:** This is also known as the "input−output method" or direct method, due to the fact that it needs only the useful output (steam) and the heat input (i.e., fuel) for evaluating the efficiency. This efficiency can be evaluated using the formula:

$$\text{Boiler efficiency} = \frac{\text{Heat output}}{\text{Heat input}} \times 100$$

$$\text{or Boiler efficiency} = \frac{\text{Heat in steam output(kCal)}}{\text{Heat in Fuel input(kCal)}} \times 100$$

$$\text{Evaporation ratio} = \frac{\text{Quantity of steam Generation in kg/h}}{\text{Quantity of Fuel consumption in kg/h}}$$

2. **Important issues:** A few points mentioned here should be noted. For enthalpy of steam and feed water heat energy the flow meter can be used using input temperature and flow rate. Similarly, the gross calorific value can be measured by WI instruments and along with flow measurement the gross heat in the fuel can be inferred. It should be noted that the firing rate should be taken into account also. This method is called direct measurement and can be done by the loss method also. For actual boiler efficiency measurement, a number of measurements are necessary.
3. **Measurement requirements:** Various measurements listed in Table XI/4.3.0-1 are necessary for boiler efficiency computation.

Boiler efficiency constantly changes and may have deviations from design values during the course of operation of the boiler. With real-time efficiency monitoring, it is always help to improve measurement by minimizing the deviation from ideal values. The computing unit can

$$\text{So, Boiler efficiency} = \frac{\text{Heat in steam output(kCal)}}{\text{Heat in Fuel input(kCal)}} \times 100 = \frac{\text{Heat addition to steam(kCal)}}{\text{Gross Heat in Fuel(kCal)}} \times 100$$

$$= \frac{\text{Steam Flow} \cdot (\text{Steam enthalpy} - \text{Feed water Enthalpy})}{\text{Faring rate} \cdot \text{Fuel Gross Calorific Value}}$$

TABLE XI/4.3.0-1 Measurement Points (min.) for Boiler Efficiency Computation

Parameter	Pressure	Temperature	Flow	Gas Analyzer (%)	Water Analyzer
Fuel	[a]Pressure T_x	RTD	Orifice: DPT, target, mass, flow		
Flue gas	Draft T_x	T/C, RTD		O_2, CO, CO_2	
Condensate		RTD	Orifice/DPT		TDS: Conductivity
Feed water	Pressure T_x	RTD	Orifice/nozzle: DPT		Conductivity, pH
Steam	Pressure T_x	T/C, RTD	Nozzle: DPT, Vortex		Conductivity

Continued

TABLE XI/4.3.0-1 Measurement Points (min.) for Boiler Efficiency Computation—cont'd

Parameter	Pressure	Temperature	Flow	Gas Analyzer (%)	Water Analyzer
Combustion Air[b]	Pressure T_x	RTD	Venturi, Aerofoil: DPT		
Make up water		RTD	Orifice—DPT		Conductivity
Blow down			Orifice: DPT or change in level		Conductivity

[a]*As applicable.*
[b]*Both primary and secondary air;* TDS, *total dissolve solids;* T_x, *transmitter.*

provide a graphical representation of trends of efficiency and associated parameters. Alternatively, the output of computed efficiency and associated parameters can be utilized in a video graphic recorder for trending. Some devices also provide recommendation regarding the optimization process under given constraints and help operating people to quickly detect causes for deteriorating conditions. Depending on the type of boiler, the amount of shift from ideal condition depends on the installation, operating conditions, including fuel, and feed water quality.

With this, the discussions on energy flow/BTU meters come to an end. Detailed discussions on boiler and utility station efficiency calculations have been presented in chapter VII of [8]. Interested readers may refer the same. We now see how flow computers function and how the data are presented in various available flow computers.

5.0.0 FLOW COMPUTERS AND DISPLAY UNITS

After going through Section 4.0.0, the reader should be somewhat familiar with the functioning of flow computing. As the name suggests, a flow computer is a computing device but it is versatile and can be functionally extended from a simple and small application to a large independent computing system capable of communicating to a plant DCS/computer. As it can be used for custody transfer/fiscal calculation, the meter proving flow computer can play a vital role in industry, depending on how it is used. Depending on the application area and scope a flow computer could be a high-integrity, standalone flow computer or have powerful building blocks integration it can be developed into a larger computing and/or supervisory computer system, e.g., Fmc[2] of FMC technology or Summit 8800 of Krohne.

5.1.0 General Discussions on Flow Computers

This discussion starts with the definition of a flow computer.

5.1.1 DEFINITION OF A FLOW COMPUTER

One may conceive a flow computer as a computation unit dedicated to flow. An electronic flow computer is an electronic device which can compute flow using various signals connected to it. An electronic flow computer defined in this manner includes a hardwired flow computer which was in use in earlier days. However, nowadays electronic flow computers are programmable and software-based computing systems. Therefore, electronic flow computer implements, in hardware platform, the software algorithms to compute flow, utilizing analog and digital signals received from connected flow meters, temperature, pressure, and other transmitters (density transmitters). Custody transfer is an important application of the

flow computer. The "cash register" in oil and gas industries is a flow computer which is typically used for custody or fiscal transfer between contracting parties.

5.1.2 FUNCTIONALITY OF FLOW COMPUTERS

Functionally, a flow computer is an electronic computational and totalizing device which needs to cater to a number of functional demands when seen from a general perspective. Such functional requirements vary by model as well as application area. Grossly these functional requirements shall include but are not limited to the following:

1. **Flow computation:** Simple mass flow computation taking into account flow, pressure temperature (for compressible single-phase fluids like steam, gas).
2. **Density computation:** Selection of a wide range of complex density computation in single-state phase hydrocarbons or density calculations for natural gas, steam, oxygen, hydrogen, nitrogen, and ethylene in selectable manner.
3. **Multiphase flow:** Computation of multiphase flow taking into account multiple signals from a variety of sensors.
4. **Custody transfer/fiscal calculation:** For fiscal calculation, computation and conversion of volume at flowing conditions to a volume at industry-defined base contract conditions utilizing specific algorithms and equations of state.
5. **Prover:** For prover from a simple proving system of single stream flow proving computation to automatic proving sequence in a larger computing system through networking.
6. **Miscellaneous other functions:** Depending on the type of flow computer chosen, it can perform many other functions which include but are not limited to the following functions:
   - Transmitter validation;
   - Report preparation for proving, fiscal data computation;
   - Proportional sampling;
   - Small batch operation;
   - Support networking.

5.1.3 DENSITY COMPUTATION AND VARIATION ISSUES FOR COMPRESSIBLE FLUIDS

Variations in density and pressure/temperature compensation issues in connection with head type measurement with DPT have already been covered in Section 2.1.9 of Chapter I. The compensation formula derivations have also been discussed therein. Also, the compensation formula has been given in Eq. I/2.1.9-6. When mass flow measurement is done with a direct mass meter like a Coriolis or thermal mass flow meter, then there will be no effect on flow measurement of compressible fluid due to density variations. Similarly, when actual volumetric measurement is made by velocity type meters, like PD meters, vortex, turbine, or ultrasonic meters, the density variations will not affect the *volume flow* measurement. However, problem arises when mass flow measurement of compressible fluids needs to be done and it is measured by any flow meter other than a direct mass meter like a Coriolis or thermal mass flow meter. From basic thermodynamics it is known that, for compressible fluid: let the medium be gas; thus for gas with density ρ: absolute pressure (P), volume (V), and absolute temperature (T), number of moles with R as universal gas constant; the relationship between volume, absolute pressure, and temperature is given by:

$$PV = nZRT \quad \text{or So,} \quad V = nZRT/P \qquad \text{(XI/5.1.0-1)}$$

$$\text{So,} \ V = m/\rho = nZRT/P \qquad \text{(XI/5.1.0-2)}$$

Here m is the mass and if M is the molecular weight of gas, then n = m/M so, Eq. XI/5.1.0-2 can be rearranged as:

$$\rho = MP/ZRT \qquad \text{(XI/5.1.0-3)}$$

$$\left[\rho \propto P \ \text{ and } \ \rho \propto \frac{1}{T}\right]$$

From Eq. XI/5.1.0-3 it transpires that, for a given gas, density is directly proportional to P/T,

i.e., a 1% increase in pressure will cause a 1% increase in density (the same applies for a decrease). A 1% increase in temperature will cause a 1% decrease in density (and the reverse applies for a decrease in temperature and increase in density also). The velocity-based instruments measure the volume directly, hence a change in pressure and temperature has a direct impact on density, i.e., when gas *mass flow* is computed by *measuring the volume* by velocity type instruments it will be more affected due to change in pressure and temperature than that for head and DP type measurement, whereas volume flow is proportional to the square root of density (as shown in Section 2.1.9 of Chapter I). This means that if there is a 5% variation in density due to a combined pressure and temperature effect then the flow measurement error due to uncompensated density will be 5% directly, whereas when measured with a head/DP type instrument it will be 2.36%.

From here it is clear that for mass flow computation of gas/steam by any of the methods without utilizing a direct mass flow meter there is a need to compensate for pressure and temperature. Such compensations are carried out in a flow computer.

5.2.0 Details of Flow Computers

In this section brief details about flow computers have been included.

5.2.1 DESCRIPTION OF FLOW COMPUTERS

As stated earlier, all flow computers are programmable and configurable devices with applications as well as configuration software packages which in some cases are proprietary though some deploy standard software. A typical flow computer with two options for operator interface systems and the field I/O unit has been detailed in Fig. XI/5.0.0-1.

Flow meters can accept signals from a wide range of flow meters (such as turbine, Coriolis, PD, orifice, Venturi, and ultrasonic), transmitters, liquid provers, flow control valves, and samplers in dynamic metering systems. Flow computers are deployed for custody transfer and fiscal

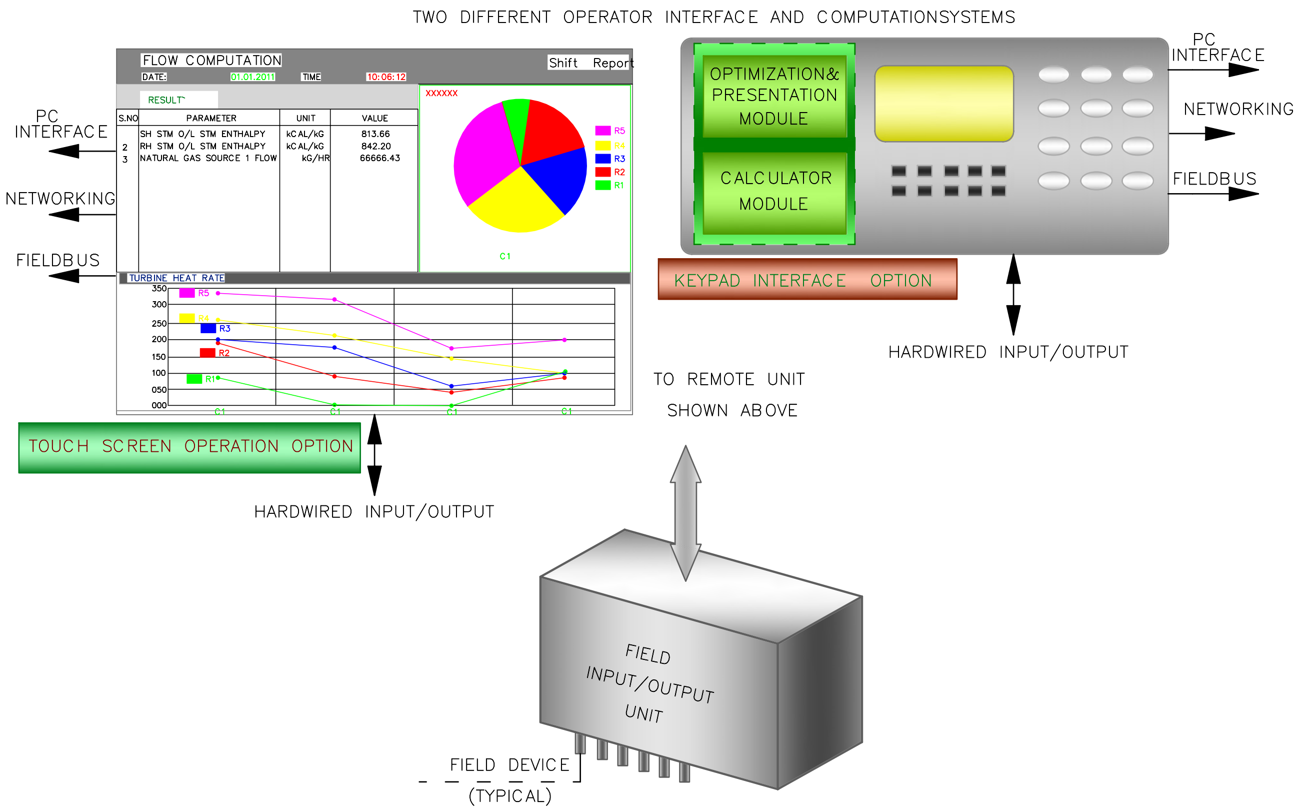


FIGURE XI/5.0.0-1 Flow computer.

applications. These flow computers can handle fiscal and metering applications for hydrocarbon liquids, dry natural gas, steam, industrial gases, and water. Flow computers designed for custody transfer/fiscal applications need not be very fast, hence in earlier designs these were slow and not economical for multiple applications. Nowadays, improved designs are available so that all calculations can be performed in <500 ms (or even <250 ms). These are capable of accommodating multiple units, e.g., Summit 8800 [9]. As many as six units can be accommodated in a single unit. Also, most flow computers in oil and gas applications support major standards like AGA, ISO, and API. Some of the functions supported by flow computers include but are not limited to the following:

1. I/O processing;
2. Display, monitoring;
3. Alarm function;
4. Transmitter power supply;
5. Mass flow/corrected volume flow, energy flow;
6. Easy operator interface;
7. Computer storage of data;
8. Logging and reporting;
9. Trending and historical trends;
10. Totalizing;
11. Transmitter validation and calibration;
12. Proportional sampling;
13. Custody transfer and fiscal applications;
14. Batch control;
15. Run switching [9];
16. High-end communication to DCS/PLC/gas chromatograph;
17. Networking.

Communication interfaces available with flow computers can cater to communication to wide varieties of applications, such as, gas chromatographs, PLCs, and DCS, as well as supervisory computers and/or standard third-party supervisory control and data acquisition (SCADA) with required safety and security. Batch control is another area where these flow computers play great role in totalising various ingredient inputs, timing, proportioning, etc. to name a few. Therefore in batch control there will be good applications of flow computation units. As stated earlier in multiphase measurements proving systems flow computation units also play great role.

5.2.2 FEATURES OF FLOW COMPUTERS

Flow computers are available in a wide variety of models. Naturally many features listed are not available in some models. The features indicated here are data from major reputed manufacturers in different models. The major features of flow computers include but are not limited to the following:

1. **Field I/O:** Scalable field I/O blocks with built-in intelligence;
2. **Processing:** Dedicated processor per I/O board;
3. **Standards:** Support of various standards, like AGA, ISO, and API;
4. **Prover support:** Automatic/statistical proving support. Small flow computer-based systems, such as a proving system, can easily be created [9];
5. **Meter factor:** Autoselective meter factor;
6. **Density:** Density inputs from various density type meters;
7. **Linearization:** Linearization of various input (>10);
8. **Display:** Different kinds of displays including textual display, trend, and graphical displays;
9. **Reporting and logging:** Printing and logging capability including alarm event log, fiscal reporting, meter proving data, graphical reporting;
10. **Operator interface:** Large color graphics screen with touchscreen membrane keypad, i.e., intelligent man–machine interface (MMI), supported by menu-driven multilingual interface. Two different types of operator interfaces have been detailed in Fig. XI/5.0.0-1;

11. **Security:** Multilevel access and authorization levels; full audit trail; separation of fiscal and maintenance data;
12. **Versatility:** Supporting removable memory, more streams, analyzers, and communications;
13. **Networking:** Supports networking, e.g., Ethernet;
14. **Communication:** Master–slave MODBUS, possible high-speed Ethernet, some also support fieldbus for system integration
15. **Software:** Supports remote MMI;
16. **Back up:** Supports standard USB flash/pen drive;
17. **Options:** Support of batch controller, PI control, meter-run motor-operated valve.

5.2.3 APPLICATIONS OF FLOW COMPUTERS

Flow computers in a broader sense can be utilized for energy flow metering as discussed in the previous section. Major application areas of flow computers include but are not limited to the following.

1. **Corrected volume/mass flow computation for:**
   - Corrected volume at base conditions for steam (saturated/superheated)/gas (ideal/general/natural);
   - Mass flow for steam/gas.
2. Single or multistream measurement.
3. Flow controls.
4. Proving (displacement/master meter).
5. Custody transfer/fiscal flow measurement.
6. Pipeline measurement and delivery.
7. Batch control, loading and deliveries.

5.2.4 SPECIFICATION OF FLOW COMPUTERS

A brief specification of a flow computer has been presented in Table XI/5.2.0-1. In this connection one should note that the specification presented here is in general form, and depending on specific application, there may be variations. It is worth noting that the specification data presented here are from reputed manufacturers and are the best possible data. Therefore, it may not match with any particular model.

TABLE XI/5.2.0-1 Specification of Flow Computer

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Display	Color graphics display screen may be with touchscreen facility; screen size ~125 to 200 mm as per manufacturer's standard (Mfr. Std.)/Backlit LCD display 2–4 lines 6–15 mm height		Two alternatives shown in Fig. XI/5.0.0-1
2	Keyboard/operator interaction	Dedicated sealed membrane type keys or touchscreen operation		
3	Power supply	240/110 VAC 50/0 Hz		
4	Transmitter supply	Yes 6–9 nos. with max limit for current (Mfr. Std.)		
5	Ambient temperature	−20 to 55°C; high humidity: 95% RH		
6	Operating condition	Temp: −273 to 800°C Pressure: Vacuum to 100,000 KPa Compressibility: Redlich–Kwong equation		
7	Enclosure	IP65/IP66 (field unit) IP54		

Continued

TABLE XI/5.2.0-1 Specification of Flow Computer—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
8	Nonvolatile memory	For setup, totals, and logs. Nonvolatile memory should normally have good retention period >20 years		
9	Battery	Lithium type for 5 years life		
10	Battery health	2–3 indication		
11	Input	Universal quantity: manufacturer's standard, logic input Input range: as indicated in op range; flow range, and input quantity: Mfr. Std.		
12	Output (HW)	Pulse, digital (potential free contact relay output), 4–20 mADC		
13	Communication link and bus	RS 485/232 with parity checks, Fieldbus supported		
14	Networking	Ethernet support for high communication. FTP possible in some cases		
15	Programmable	Algorithm for ideal gas, natural gas, saturated/super-heated steam		
16	Built in table	Specific gravity, enthalpy		
17	HVAC capability	Heating, cooling, and conditioning		
18	Data Logging	Storage of data to produce real historical trends, logs, hourly, daily, weekly, or monthly		
19	Modes of operation	Steam (ASME) and gases various standards mentioned above in Section 5.2.2		
20	Calculation	Standard volumetric flow, mass flow, density, compressibility calculations based on Redlich–Kwong equation, NX-192 equation Steam-specific weight and enthalpy as per ASME, energy, peak energy and efficiency in addition to sum, difference square root		
21	Accuracy	±0.1% AR or better		
22	Resolution	8 Bit (min)—as per Mfr. Std.		

Batch controls, filling, and dispensing functions are also part of the flow-measuring system. We next look at this after concluding the discussions on flow computers with various display and operator interface types.

5.3.0 Various Display Units and the Operator Interface

Rate and totalized flow indications are very pertinent o flow measurement and control. Any discussions on flow would not be complete

without a discussion on rate and totalized flow indication/displays.

For flow measurements and control, rate and totalized flow indication is extremely important (associated with flow meters also). In this section short discussions shall be presented on various types of rate and totalized displays with flow meters. There are various kinds of indications available. The factors which influence the display selection include but are not limited to the following:

1. **Type of input:** There are various kinds of inputs, such as 4–20 mADC, pulse input;
2. **Indication type flow measurement:** Rate flow, rate flow and totalized flow, totalized flow;
3. **Continuous process controller:** Set point/measured value, deviation, final control element status, alarm set point, and others. Also there will be an operator interface for operational parameter setting;
4. **Batch controller:** Keys for: start, batch, pause, and stop; indications: rate flow, batch total, grand total, batch count, preset for multistage/batch stage indications;
5. **Totalized indication:** Number of digits (application- and manufacturer-dependent), resetting, password protection (optional);
6. **High-resolution operator interface:** In some cases there is a high-resolution graphic screen with displays for trend display, mimic overview display, etc. There may be touchscreen facilities available in place of keypads or pushbuttons. Operator menus and access-level interfaces are also available.

In addition to these there will be indication and operator interfaces for auto/manual selection, raise/lower, actuator statuses, and number of stages (manufacturer standard). Such displays and actions are implemented by indicators and keypads or through graphical displays with a touchscreen, as indicated above.

6.0.0 FLOW IN BATCH CONTROL–FILLING AND DISPENSING

In this section short discussions on three different issues involving flow measurement will be addressed. These are:

- batch controllers;
- filling machines;
- dispensing machines.

In each of the sections the main focus will be on measurement and automation related to flow measurement. Brief coverage of terminal automation is also included. The discussions start with batch control and the role of flow measurement.

6.1.0 Flow in Batch Control

If you look at a phial of medicine or bottle of cold drink you will notice that in each of these phials or bottles there will be something called the **batch** number date of manufacturing, as well as the date of expiry, which are printed either on the container or a label pasted on the container. Here the batch is important. This signifies that this product has been produced in a batch. So, *what is this batch and why it is so important?* We now look into the batch process.

1. **Plant process:** Plant processes/productions can be categorized as discrete process, continuous process, and batch process. Each of these is briefly defined below.
   - *Discrete process:* In a discrete process, finite quantities of discrete parts/products are manufactured, i.e., manufacturing of smartphones, cars, airplanes. This is not much of interest for process control, it is more related to manufacturing.
   - *Continuous process:* A continuous process produces a continuous flow of free-flowing product, e.g., thermal/nuclear power generation or a paper plant. All flow meter types

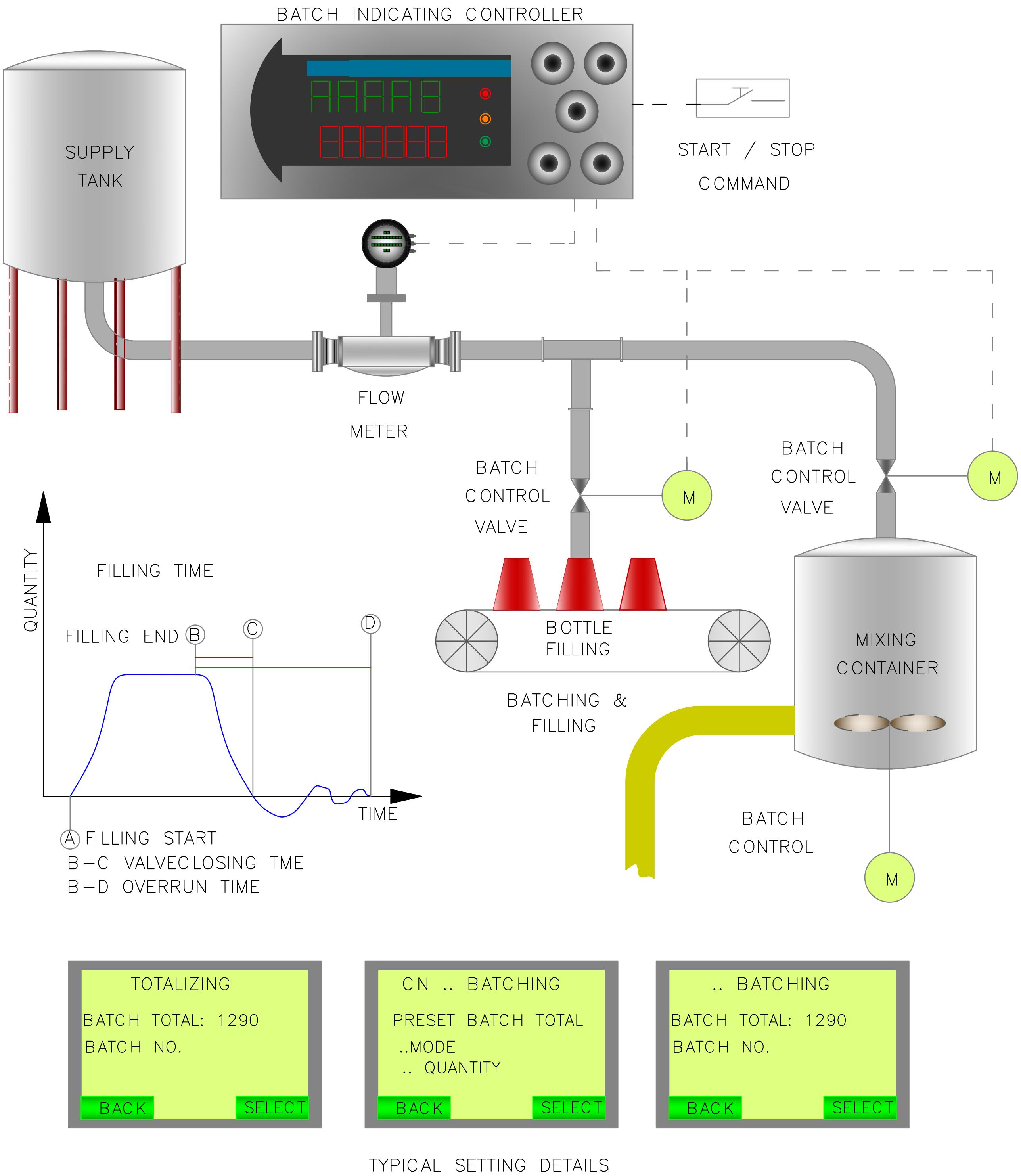


FIGURE XI/6.1.0-1 Flow in batch control and filling. *Developed based on an idea from Flow Meters for Batch Dosing; Application Description AG/FB114-EN Rev. A, ABB Limited. https://library.e.abb.com/public/634cbfaa510a476a81f464cec9b6d3d1/AG_FB114_EN_A.pdf.* Courtesy: ABB.

discussed previously can be applied to a continuous process. Continuous process could be a connected continuous system (such as thermal cycle in a fossil fuel power plant) or nonconnected system (such as cement plant where kiln can run without raw mill/cement mill in operation). The continuous process is a rather standardized process. In the case of a batch process special requirements apply.

- *Batch process:* A batch process is distinctly different from a continuous process. This process involves production of a *finite quantity* of free-flowing product. In chemical process plants, the batch process involves discontinuous "charge-wise" production of chemical produce. A major standard for the batch process is ISA 88. According to ISA 88 a batch process is "*A process that leads to the production of finite quantities of material by subjecting quantities of input materials to an ordered set of processing activities over a finite period of time using one or more pieces of equipment*."

2. **Batch control:** Batch control activities and functions provide a means to process finite quantities of input materials by subjecting them to an ordered set of processing activities over a finite period of time using one or more pieces of equipment.

   Pharmaceutical production, food processing plants, and cold drinks/beverage plants fall under this category. In addition to production storage, bottle filling also requires flow measurement, hence it demands special attention which will be covered in this section from a flow measurement point of view [10]. However, to understand a batch process it is necessary to know a few related terms such as the recipe, batch process model, unit, etc., which in this limited space it is not possible to cover. The interested reader is referred to detailed discussions on the batch process in line with ISA 88 described in Section 3.0.0 of Chapter VI of Plant Hazard Analysis and Safety Instrumentation Systems [10].

3. **Flow in the batch process:** Flow in a typical batch control has been shown in Fig. XI/6.1.0-1. In many cases filling and batch control go together, so for idea about the role of flow metering in filling, filling has also been included in this figure.

A brief discussion of batch control in this section covers the following issues:

- Functional details of batch control;
- Operation of batch system;
- Features of batch controller;
- Specification of batch controller.

  Detailed discussions on batch process and batch control systems have been presented in section 3 of Chapter VI in [10]. Interested readers may go through the same for details on batch process and batch controls. The discussion starts with functional details of a batch controller.

6.1.1 FUNCTIONAL DETAILS OF FLOW IN A BATCH PROCESS

As stated earlier, the food, beverage, and pharmaceutical industries are classical examples of batch processes. Without going into the details of the process it can be argued that the measurement and control of fluids in batch processes is critical and cannot be overestimated in achieving the desired final product quality, with the highest yield, and at the lowest cost. In a batch process it is necessary to dose, pump, mix, and blend various fluids and solids, such as liquid, air, and gases and solid ingredients, e.g., cheese, fruit juice, and beverages/cold drinks. In such cases it is necessary to blend and mix a ratio-based ingredients and/or use blend line control systems. In smaller batch processes, the required components are dosed and mixed in containers one after the other using suitable flow meters [11]. In the case of large batch process systems, PLC/DCS can be deployed. However, in smaller systems, large investments may not be justified, so they go for available intelligent smaller batch controllers, e.g., small cold drinks bottling plant or a small confectionery plant. However, there will be a need for flow measurements in all these cases. Therefore, it is important that suitable flow meters are selected based on the application. When selecting a flow-metering device for batch process, one of the first considerations is always

the process media: air, gas, steam, or liquid [12]. This is important as some work better in liquid than in gas and vice versa, e.g., a PD meter is very well suited to liquids, whereas a vortex meter is well suited for steam applications. Apart from this sizing, accuracy requirement, calibration, installation, maintenance issues, cost, etc. are other important factors, as already discussed in this chapter. Based on these facts, major flow-sensing technologies used in connection with batch processes include but are not limited to:

- Head type measurement (Chapter II);
- Variable area (Chapter II);
- Positive displacement (Chapter V);
- Electromagnetic (Chapter V);
- Turbine (Chapter V);
- Ultrasonic (Chapter V);
- Vortex shedding (Chapter V);
- Coriolis mass (Chapter VI);
- Thermal mass (Chapter VI);
- Process batch weigher (Chapter VIII).

In the list of technologies mentioned above, the final one pertains to solid flow and has been discussed in detail in Section 8.0.0 of Chapter VIII, hence it is not repeated here. Each of these technologies has some advantages/disadvantages for specific applications. Let us take the example of Fig. XI/6.1.0-1.

In this figure typical dosing from the supply tank along with the filling system has been shown to indicate that the same controller can be used in dual purposes. Here two separate processes have been shown which need not necessarily be at the same place. In one case in a mixing chamber two liquids are mixed, for one component the flow meter has been shown (the other line to the mixer could have similar) but with a common batch controller. In the other case the filling operation is carried out based on measured flow with the help of the controller. As shown in the figure, getting a start/stop command from the batch controller would be active to allow the motorized valves to open so that the required quantity of ingredient would pass through. In its simplest form an internal presetting counter inside the flow meter (e.g., such as an electromagnetic flow meter) could be used to carry out the dosing or ingredient addition into the process. As stated above, the process can be started through an external start contact and stopped via the counter's output contact for the valve operation. This process may not be very accurate and is not always possible. When preset counter gives an output for the valve to close, it will take some time to close and during that period fluid will be passing to the system. Thus, there will be excess flow or overrun of fluid dosing. This is stated here in connection with flow meter contact to reset, but is applicable in all cases. The situation has been explained with the help of the curve in Fig. XI/6.1.0-1. When the start command reaches a point, e.g., **A**, the valve opens, allowing the flow to pass, on the stop command (or the preset counter operates the stop command) is issued at point **B**, on account of closing time of the valve (which is more in electrical actuators) it will close at **C** but in fact it will settle at **D**. Here B—C is the closing period of the valve and the actual overrun is B—D. During this period fluid will be dosed into the system. This is overrun. For accurate measurement and control, there must be some means for overrun correction/compensation. In automatic overrun correction, the meter/controller measures the quantity that continues to flow after the close command to give excess dosing. Based on calculations, the length of time by which the meter's close command should be moved forward is discovered for subsequent cycles in order to ensure accurate dosing. From here it transpires that overrun compensation is a feature of a batch controller and should be included in the system. Start/stop commands, as discussed above, can be from manual pushbutton contacts or from auto contacts, along with other operating conditions from control systems like PLC/DCS or any other control system. The batch control system discussed above is a simple one but it may not be so in reality. In real systems, suitable batch controllers are used to cater to various presetting counters as necessary for the process. These precounters are program-controlled with suitable operator interfaces. There are several displays for these batch controllers as shown in Fig. XI/6.1.0-1 for familiarization purposes. One thing to note is that out of the batch information, it also shows the

totalized figure. This means the batch controller must have the capability to totalize the flow over a preset time for which automatic compensation of overrun is applicable. As shown in Fig. XI/6.1.0-1, the flow meter, in conjunction with the batch controller, can be used for filling purposes also. Therefore, batch controller function can be used in filling machines also. Prior to going to operational aspect of a batch controller it is better to have a clear idea of the few functional issues related to batch control systems. The major such functional terms are explained below so that the functionality of the batch control system can be understood.

1. **Overrun and auto action:** The overrun issue has been explained above. Based on previous batches it is possible to automatically compensate for any overrun caused due to slow valve closing.
2. **Batch count:** For batch quantity, up and down counts are provided and displayed.
3. **Batch limit:** It is possible for authorized personnel to set a maximum batch quantity that can be programmed during set-up so that later it cannot be changed by the operator unless the set up is changed totally.
4. **Flow failure:** In case there is a failure of the flow meter, i.e., the flow signal is out then it will be annunciated through the output contact and the batch may be suspended.
5. **Remote start/stop and interlock:** As indicated earlier, a remote manual contact (may be a remote pushbutton) or auto interlock is used to initiate start/stop operation. Also, it is possible to restart the batch process through a process interlock and/or preset time.
6. **Start and end of batch:** The start/run/end of the batch process are indicated in the front panel. In addition to this there will be a digital output for the end of the process.

We now look into flow meter operation in various batch control processes.

6.1.2 FLOW METERS IN BATCH PROCESS OPERATIONS

It is needless to repeat that flow meters are extensively used in batch processes. In this section a few flow measurement examples related to batch operations are described.

1. **Cheese preparation:** For food processing pertinent to cheese preparation accurate measurement of air for proper growth of yeast is an absolute necessity. Measurement of air flow in a cheese processing plant is shown in Fig. XI/6.1.0-2A. Here air flow is measured at the air inlet and connected to the batch controller to perform its function.
2. **Juice preparation:** In the case of canned juice, a few ingredients are mixed in a mixing container or reactor and after mixing for a preset time the same is filled into bottles, as shown in Fig. XI/6.2.0-1. In this case for each batch a fixed proportional quantity of each ingredient is supplied to the mixing reactor. A batch controller, along with flow meters with totalizing and preset contacts, are necessary for the batch operation to take place.
3. **Pharmaceutical batch operation:** In the production process for fatty alcohols and many other chemicals in pharmaceutical industries these are prepared with the use of hydrogen as a circulating gas. In many such processes hydrogen fulfills a double role as a raw material and also as the primary carrier medium. In this process normally there are two lines: the high flow line and low flow line. Each one is used one at a time in stages and in sequence. Therefore, in both high flow as well as low flow lines, flow meters are deployed and each of the two flow meters has a different flow range. The associated batch controller decides on the batch sequence or high or low flow line selection, and at the same time the range selection for the measurement values for subsequent calculations and operations. A typical similar application is shown in Fig. XI/6.1.0-2B. A variety of flow meters with various outputs can be used.
4. **Nitrogen blanketing:** This is a common operation in batch processes with flow meters and valves. Inert gas (N_2) blanketing is a low-pressure inert gas (e.g., N_2), which is injected into the vapor space of a storage tank above the liquid. A flow meter is used to monitor

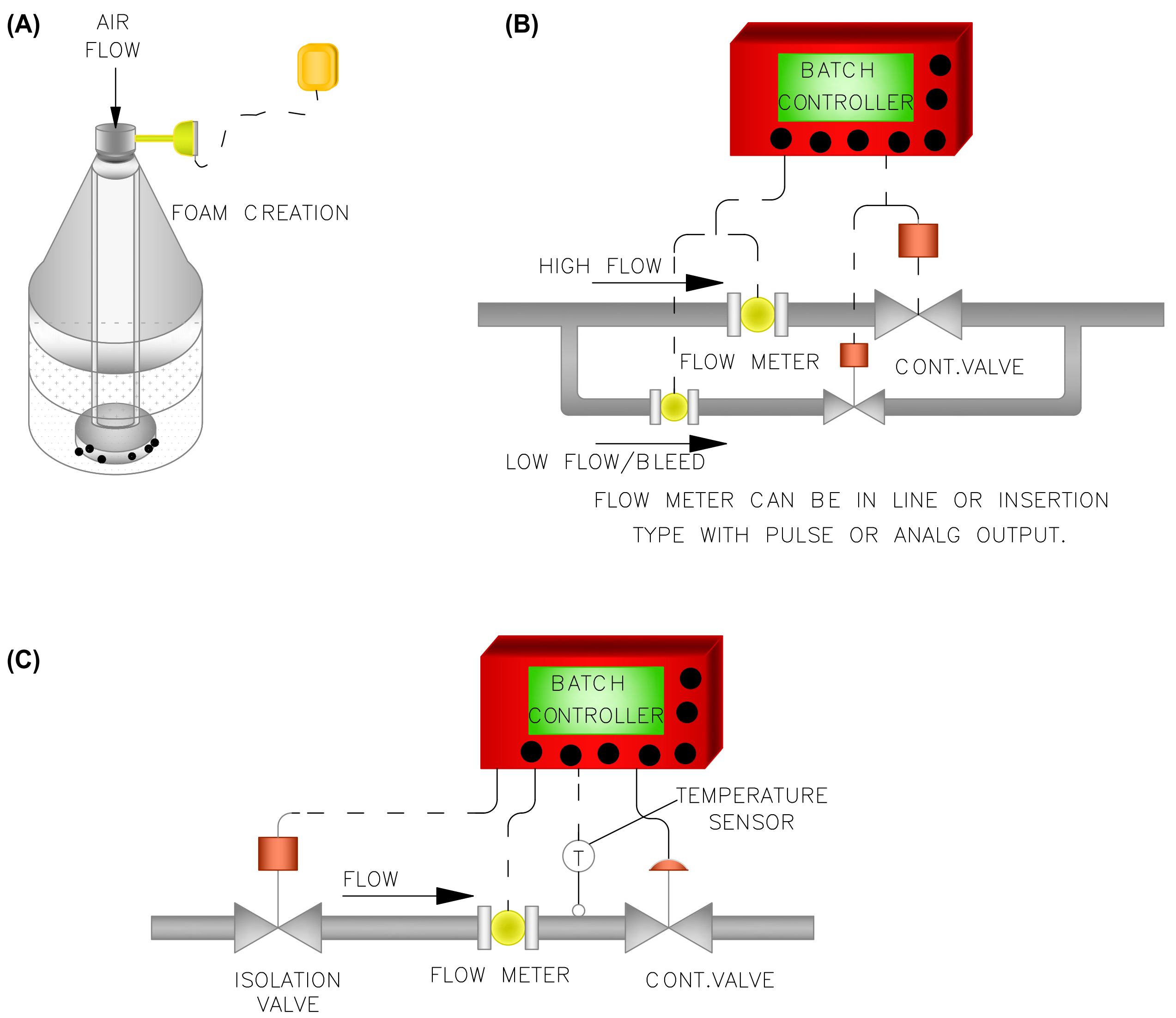


FIGURE XI/6.1.0-2 Flow measurement in batch operation. (A) Batch operation and air. (B) Batch operation in high and low flow. (C) Flow measurement and batch operation. *Developed based on A. Womack, Flow Measurement and Control for Small Line or Batch Processes, Technical Publication, Fluid Components International LLC. http://www.fluidcomponents.com/assets/media/Articles/FlowMeasurement_1207.pdf. Courtesy: Fluidic Corporation International LLC.*

and regulate the flow of inert gas, with pressure monitoring, into the tank. Flow switches are used for leakage detection.

5. **Flow monitoring and regulation:** A typical flow measurement and flow calculation in batch operation is shown in Fig. XI/6.1.0-2C. In batch processes, flow measurements are carried out for smooth operation. The flow meters may be in-line flow meter or insertion type and/or head type with both analog/pulse output, or these can be connected through fieldbus/Hart connections. Depending on the application there can be temperature compensation as shown in Fig. XI/6.1.0-2C. Normally there will be a control valve for flow regulation connected to the batch controller. There may

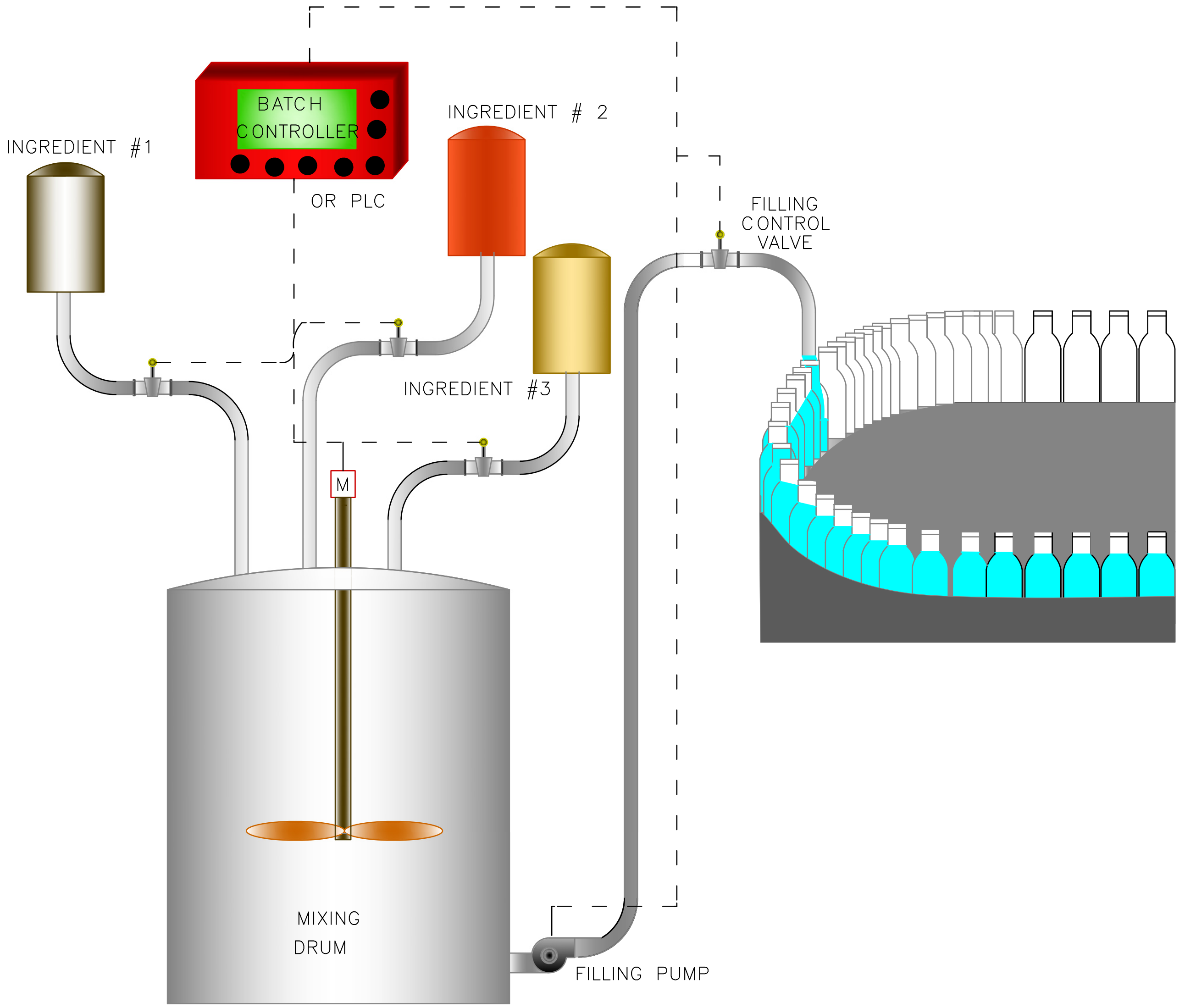


FIGURE XI/6.2.0-1 Automatic bottle filling.

be an isolating valve also. There may be two regimes of operations or there may be a bypass line as shown in Fig. XI/6.1.0-2B. When the K factor of the meter is known, then volume can be calculated as volume = pulse/K factor, so volume flow can be calculated by frequency/K factor. These are applicable for turbine/PD meters, etc. The output of the batch controller can be contact output to drive valves, pumps, etc. Additionally, it is necessary to totalize flow to carry out batch operation.

Now we look into the details of batch controllers.

6.1.3 FEATURES OF BATCH CONTROLLERS

There are a variety of batch controllers available. Each of these has different features and associated costs. In this section brief discussion on the features of batch controllers is given. Some of the important features and functions supported are listed below.

1. **Input−output types:** There are analog/frequency inputs from flow meters. They accept a number of other inputs, such as temperature input (for compensation), binary inputs

(for permissive and interlocks), etc. to name a few. In most cases input types are universal, such as 4–20 mADC, T/C, RTD, etc. Some systems can exchange data through a fieldbus. Normal outputs are binary/relay output, however, in some cases supporting PI control can deliver 4–20 mADC. The number of configurable outputs available varies with the model.

2. **Volume corrections:** Batch controllers accept density and temperature inputs for volume correction. Volume corrections for petroleum products and user-defined fluids are quite common. Quadrature flow input to ISO 6551 level B pulse security is possible.
3. **Other control and common functions:** For proper operation a number of additional functions are performed in programmable batch controllers. These include but are not limited to the following:
   - *Totalizing and counting functions:* Gross, net, or mass total;
   - Easy access and configuration of multiple set point adjustments;
   - Detection of no flow, leakage, and error;
   - Multiple stage controls;
   - Preset action;
   - Manual on/off;
   - Unloading modes;
   - Standard computation;
   - Logic/interlock functions.
4. **Operator's interface:** There are a variety of display forms and modes with built-in push buttons/touchscreen operation. The display type varies from a backlit LCD display to high-resolution graphic displays with touch screen facilities and START/STOP/RESET SET FUNCTION buttons/keys.
5. **Communication:** Serial port with selectable protocol, to support RTU and printing. Some support fieldbus in larger systems.
6. **Miscellaneous other functions:** Data storage function, USB transfer, input signal validation, ranging and linearization function, security checks, communication checks, external permissive, and interlocks.

6.1.4 SPECIFICATION FOR BATCH CONTROLLERS

A brief specification of a batch controller has been presented in Table XI/6.1.0-1. It is worth noting that the specification data presented here are from reputed manufacturers and the best possible data. Therefore, it may not match with any particular model.

TABLE XI/6.1.0-1 Specification of Batch Controller

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
1	Display	Similar to Sl. 1 Table XI/4.2.0-2		
2	Key/operator interface	Similar to Sl. 2 Table XI/4.2.0-2		
3	Power supply	240/110 VAC 50/0 Hz		
4	Transmitter supply	Yes, around six with max limit for current (Mfr. Std.)		
5	Ambient temperature	Similar to Sl. 5 Table XI/4.2.0-2		
6	Enclosure	IP65/IP66 (field unit) IP54		
7	Nonvolatile memory	Similar to sl. 8 Table XI/4.2.0-2		
8	Battery	Similar to sl. 9 Table XI/4.2.0-2		
9	Input	Refer to Subsection 6.1.3.1		

Continued

TABLE XI/6.1.0-1 Specification of Batch Controller—cont'd

SL	Specifying Point	Standard/Available Data	User Spec.	Remarks
10	Output (HW)	Refer to Subsection 6.1.3.1		
11	Communication link and bus	RS 485/232 with parity checks, and MODBUS protocol and others as per manufacturer's standard. Fieldbus supported possible		
12	Data Logging	Storage of data. Refer to Subsection 6.1.3.5		
13	Modes of operation	Batch control/ratio control. Selection of various modes of operations. Volume correction and linearization		
14	Accuracy	±0.1% AR or better		
15	Resolution	8 Bit (min)—as per Mfr. Std.		

We now look into the filling machines where there will be applications of different kinds of flow meters as well as metering pumps.

6.2.0 Filling Machines

Filling machines are often referred to as fillers. These are used for packaging materials produced in different process plants and other industries. It is needless to say that the sale of products is very much dependent on how it is packaged. Apart from attractive packaging to gain the attention of the consumer to improve sales, packing has other attributes, i.e., handling of the product both during filling at the place of production as well as by the consumer. The products can be in various forms, such as solids (e.g., cement, detergent powder), liquids of different viscosities (e.g., creams, mascara, mayonnaise, lotion, fruit juice or mineral water). Similarly, depending on the type of product (liquids, dry powders, thick fluids) to be filled and container (different bottles, vials, ampoules), the packages can be of different kinds from a small pouch (e.g., shampoo/ketchup), bottles (glass/plastic), or drum- or powder-filling machines, i.e., different container types with different shapes and sizes. Naturally there will be a variety of machines deployed for this purpose. From an automation point of view there can be classification of filling machines, e.g., fully automatic or semiautomatic. Some of these machines use a flow meter, while others may use a metering pump for the same purpose. Also, some are sold in terms of volume units, e.g., 1 L of mineral water, and some are sold in terms of weight (mass), e.g., "X" oz. of ketchup. On the other hand, solid flows like those for grains, cement, fertilizers, etc. use completely different kinds of systems and these are better known as bagging plants. Loss in weight, for example, is a common system in solid filling and dispensing and these have been discussed at length in Chapter VIII. Therefore, in this section the discussions will be mainly on fluids. Since various flow meters and metering pump types have been discussed at length already, here the application side is concentrated on. *But* ***why packaging machines?***

Packaging machines in any form speed up product filling or dispensing tasks in industries to save not only time through their efficient use, but also improve the business by way of cost-saving due to a lower number of labor hours and cost-cutting of packages in modern industries, as well as making packaging convenient and attractive. These machines are multitasking in nature. They can also perform various other functions like washing of containers, sealing of containers, etc. Therefore, a single filling machine enables the implementation several other tasks which would otherwise require buying other

machinery and thereby increasing the production costs. Added to this, modern automation technologies have reduced the requirement for labor in packaging, which is an added factor that cuts the cost of packaging in modern industries.

6.2.1 STANDARD ISSUES RELATED TO FILLING MACHINES

There is no limit for the type of materials for packaging, in terms of shape, size, quantity, physical properties, etc. Packaging each of these materials is not an easy task. Naturally, most manufacturing machines for packaging solutions are customer need-specific, i.e., they are developed, modified, and built specifically for the project and product at hand. This is more so in the case of liquid-filling machines because for solids like cement bagging, standard machines are available. However, there are some standard features based on which these machines are developed and later modified for specific uses. Some of these standard features include but are not limited to the following:

1. **Materials of construction:** Most of these machines are manufactured using stainless steel because it is suitable for the majority of products. With solid, robust stainless steel longer life with less wear and tear is expected from the machine with everyday use and it ensures consistent and reliable performance as well. However, some materials like acids, bleaches, and other chemicals do not go well with stainless steel so in these cases nonmetallic substances, like HDPE/PVC, etc., can be used if mechanical forces are withstood by the material.
2. **Vision systems:** The vision system generally refers to the system which extracts desired features through digital images. The vision system is applied to the industrial packaging system to automate the manufacturing process [mainly by automated visual inspection (AVI)]. Vision systems use sensors to guard against container (bottle) jams and ensure the correct number of containers are in place before a fill begins. These vision systems also helpful in ensuring filling performance and avoiding spills, downstream bottle jams, and backups. The vision system, which may be different for different production lines, is included in the filling system for smooth operation.
3. **Operator interface with control system (PLC):** The packaging/filling system is not very complicated, and so simple controls are always preferred. It is generally found that for each packaging line there is a complete centralized control system with a suitable operator interface. In the case of several lines, these controls may be connected to a centralized monitoring and supervision system. The amount of automation and control capabilities within the main system and local lines may vary from facility to facility. Normally, smaller PLCs, along with a central PLC system, are deployed for such purposes. PLCs can be used to control all delays and duration times for things like indexing, filling, and pump activation. Manual controls can be in place for troubleshooting and bottle changeover. In addition to this there may be central electrical controls for control of the conveyor/turntable, etc. Smaller PLCs are usually connected to the central control in a master−slave configuration. Nowadays control systems in most cases have touchscreen technologies at the operator's interface, while in smaller systems membrane keys/miniaturized pushbuttons are also found. However, for larger systems in most cases touchscreens are used.
4. **Recipe screen:** There are many plants where a number of products are produced and for packaging the same production line is used for different products in different batches. The product recipe screen is an important operator interface and almost a standard feature in all filling machines. The recipe screen takes all of the settings associated with a specific product and particular container. Such information would include but is not limited to: indexing times, fill times, pump speeds, container size, etc. Here product-specific information is stored and called on as and when required.

5. **Adjustments:** A quick changeover from one container size to another on a filling machine is not only convenient, but can save both time and money in the long run [13]. A quick changeover facilitates height adjustment and helps to maximize the run time of the machine for efficient production runs.

6.2.2 GENERAL FEATURES OF FILLING MACHINES

In the above section a short explanation of standard issues related to filling machines has been presented. As indicated therein, on account of the limitless varieties of materials for handling there will be wide varieties of machines for specific uses. However, the following are a few points indicating that the features normally encountered in filling machines (especially liquid-filling machines). Such features when applicable can be useful in selecting a filling machine.

1. Various flow meters and supports:, e.g., Coriolis flow meters, metering pumps;
2. Fill head valve;
3. Intelligent control, such as a PLC control system;
4. Graphical display with touchscreen/keypads;
5. Product settings from operator interface;
6. Tool-less adjustments and rapid changeover;
7. Clean product flow path (no dead spots, gaps);
8. Accommodation of a variety of containers in all shapes and sizes;
9. Provides operators with easy and quick volume adjustments;
10. Easy container and product changeover;
11. Wider range of product size;
12. Reliable and high-accuracy filling;
13. Capable of handling a wide range of product viscosity;
14. Waste-free filling up.

6.2.3 DESCRIPTION OF TYPICAL FILLING MACHINES AND SYSTEMS

In this section some examples of liquid-filling and solid-filling (e.g., capsules) machines are presented to give an idea of the different types of filling machines. Various types of flow meters can be used for liquid filling. These can be volumetric and gravimetric.

1. **Volumetric:** When the discussions in Section 6.1.0 are recalled it can be seen that the filling machine may need the help of a batch controller as detailed in Subsection 6.1.2.1 and depicted in Fig. XI/6.2.0-1. This figure shows automatic bottle filling for, e.g., juice bottles. Here the batch controller could basically be a PLC specifically programmed for the application or could be an intelligent embedded control system. Flow meters (not shown) of suitable type, e.g., PD/turbine flow meters, could be installed in each ingredient line. Sometimes a change in the level/time can be used as a regulating parameter. However, it is better to use flow meters and for each line to use totalizing in a so-called batch controller/PLC. Here the flow meter may be a PD meter.
2. **Gravimetric:** On account of its multivariable measurement capability the Coriolis meter is preferred in many applications, like the paint industry, as shown in Fig. XI/6.2.0-2. Coriolis does not require density compensation, and at the same time it can give the volume and density. Also, it does not require straight length or have any special installation requirements. Earlier paint industries used volumetric displacement pumps to pour the paint, which was placed in a load-sensing platform, which first senses the weight of the can then weighs the can when filled with paint. When the can reaches the preset weight the flow from the filler is stopped. However, the measurement system was cumbersome as spillover would make an inaccurate set point. So, in many paint industries, Coriolis in conjunction with PLC is used. There are filling and blowdown valves that both operate by PLC. In food industries, gravimetric filling is also used. They use desired numbers of sanitary Coriolis flow

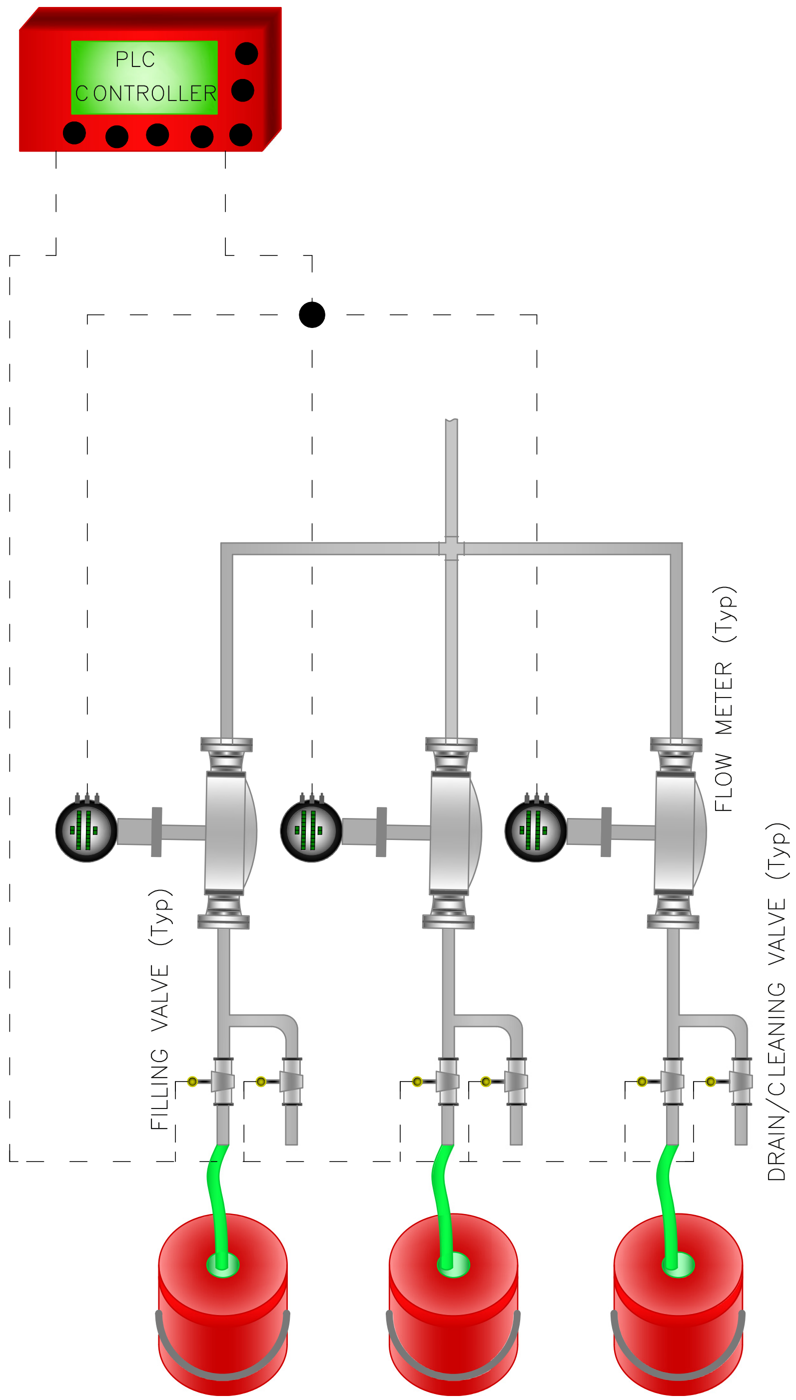


FIGURE XI/6.2.0-2 Use of flow meter in filling machine.

meters with the necessary fittings. Bottom-close fill head with pneumatic diving fill heads is used. Normally 316 steel is used as for easy cleaning.

Capsule filling in the pharmaceutical industry requires completely different types of machines to precisely fill many toxic materials into small capsules in small quantities.

In bottle-filling plants visual inspection is an important system. A visual inspection system is deployed to ensure the proper labels and bottle caps are applied to each product in the

correct locations. Defective products are discarded before packaging. Special features of visual inspection include high-speed inspection in the customer inspection enclosure, out-of-specification product culling, etc. This is beyond the scope of this book, but is outlined here to complete the discussions. Flow meters also find applications in dispensing systems discussed below.

6.3.0 Dispensers

The dispensing process, like filling, also uses flow measurement and control. One of the most common dispensers most of us are well aware of is the fuel dispenser in fuel stations. This is used for filling fuel into cars, trucks, buses, etc. Basically, the issue in both filling and dispensing is the same, taking out a portion of material from the storage, the only difference being that in the case of filling the filled container is measured, while in dispensing the measurements are done at the dispensing end. So far as the purpose of quantity measurement is concerned it is the same, only difference is in the way it is implemented for the specific application. It will be clear from these two examples: in a beverage dispensing machine dispensing liquids including water, beer, and soft drinks, a turbine flow meter is used to measure the quantity dispensed, i.e., liters/minute, whereas the end user refers to these as a 1 L bottle or a pint, etc. Similarly, when fuel is dispensed in a fuel station it is measured by a PD meter and the unit is liters/minute, whereas we refer to these in terms of a full tank, half tank, etc. Therefore, the filling and dispensing processes goes hand in hand, only the flow measurement method may be different. Like filling, dispensing can be volumetric as well as gravimetric. In the pharmaceutical and many other industries it has been found that both types of dispensers are used. When low-quantity precision multicomponent dosing is necessary gravimetric dosing is used in the weighing chamber from where materials are sent to the selected destination. This system uses modern feeding techniques and microprocessor-based control for light-weight chemicals, to ensure maximum reliability, safety, and accuracy. For powdery materials gravimetric dispensing is preferred. For large-quantity dispensing, volumetric dosing is used for the selected destination. This system combines a high-capacity, flow-adjustable gear pump, accurate magnetic flow meter, and microprocessor-based control for fast transfer of high-volume chemicals. Material types also dictate the type of dispensing preferred, e.g., powdered materials are normally dispensed through gravimetric means as seen in pharmaceutical industries, whereas, gum, glue, etc. are normally metered and dispensed in volumetric form. It is better to look into some examples of dispensing of different material types. It is needless to say that it is not possible to cover all types of materials; a few examples are cited only to give an idea of material dispensing and how it is associated with flow measurement.

6.3.1 VOLUMETRIC DISPENSING

There are certain items which are normally dispensed by volumetric means. In such cases volumetric flow meters, like PD meters and turbine meters, are used. As already discussed above, Coriolis meters can give multiple outputs, so they can be used in both cases. Cost is the prohibitory factor in some applications, e.g., dispensing alcohol in a bar! Let us now look for some examples of volumetric dispensing.

Dispensing of fuel: In a fuel station the fuel dispense function is carried out by the fuel dispensing pump. Here flow measurement is carried out mostly by a four-stroke piston type corrosion-resistant SS PD meter with associated electronics to give encoded pulses (normally 100 pulses per liter) for direct counting and display in electronic backlit LCD/LED displays of the dispensing machine as totalized flow over the time the dispensing pump is on. These dispensing machines are nowadays equipped with a microprocessor-based control and computing system. Basically, flow meter electronics convert the meter movement into a rotary encoder as discussed in Chapter IV. In older fuel-dispensing pumps, the meters were physically coupled to reeled numerical displays (moving wheels or

cylinders with numbers on the side). In this type of dispensing machine, the desired quantity to be dispensed is set, and after the set value is dispensed the pump will be cut off from the meter signal. Often, in addition to display of the dispensed quantity, there may be provision to display the price for the quantity dispensed. In most cases the front display may be reset but the record remains, i.e., there will nonresettable totalizing functions with more digits to keep the record of the quantity of fuel dispensed.

Dispensing of drinks: Turbine meters are often used for dispensing beverages and drinks like liquors and soft drinks. These are normally done in the range of 10 L/min (other selectable ranges are available). Normally these meters use nonmetallic wetted components best suited for the metering of food-based products and even ultrapure water. The precision turbine rotates freely on robust sapphire bearings in a suitable chamber. Turbine rotation is measured by a Hall effect detector/magnetic pick up (discussed in Chapter X). The output is a stream of NPN pulses that are directly interfaced with the electronic display. This output suitably interfaces with the electronics of the dispensing machine with suitable indications and presettings. Bottle filling, as already discussed in Subsection 6.2.3.1, will follow. In some bars they also used volume dispensing of alcohols and for preparing cocktails. In such cases, conduit connected systems are used to pour alcohols easily and quickly with the help of an electronic control which accounts for precision quick pouring and registering the quantity of each brand dispensed.

Dispensing of sealant/adhesives: Sealants and adhesives are generally very abrasive, viscous substances with high solid content. Sealants and adhesives are dispensed in very small quantities under very high-pressure conditions, from more than 400 barg. In these applications, pulses from a flow meter are supplied to the control system in order to precisely dispense the correct amount of material. PD meters are best suited for the application of dispensing sealants and adhesives with faster speed of response, high resolution, and excellent repeatability. PD meters use thermoplastic materials. The design should be such that there will not be much of a pressure drop in the line.

6.3.2 GRAVIMETRIC DISPENSING

There are certain items, like powered materials in pharmaceutical industries, food grains, or cement that are normally dispensed in gravimetric forms only. In such cases gravimetric flow meters such as weigh scale, platform weigher are deployed. In this method, loss in weight (LIW) or gain in weight (GIW), as discussed in Chapter VIII, will be used. In many of these cases Coriolis mass flow meters (Chapter VI) can be used if cost and technical applications allow.

Gravimetric oil dispenser: These are mainly used for engine oil, transmission oil (with high viscosity also), and even for diesel oil. Pneumatic pump and filling and dispensing valves are used for this type of dispensing machine. They are often offered with float switches at the storage unit to prevent spillover. They are equipped with a weighing hopper with a suspended load cell. The operation of dispensing is based on loss in weight (refer to Chapter VIII) of the hopper method in conjunction with a pneumatic filling valve. Machines have a front panel for carrying out the operation and programming by authorized personnel. There are LED/backlit LCD displays and a membrane (or other type of) keypad. The system is controlled with the help of an embedded microcontroller with nonvolatile RAM (backup memory data). Cumulative totalizing display and batch total displays are common two-line displays for the machine. Apart from these there will be a push button station for operation of the pump, etc. An accuracy of up to $\pm 1\%$ FSD is not uncommon.

Batching and dispensing systems for rubber industries: This type of batching and dispensing machine, with overhead tanks, is used in rubber industries. The machine consists of weighing hoppers and a pneumatic butterfly valve vibrating feeder (for carbon) for dispensing carbon oil and other ingredients into the intermix.

Weighing hoppers working on the loss in weight (refer to Chapter VIII) method re deployed here for flow measurement. They are controlled by dedicated PLC with facilities to communicate outside. There are LED/backlit LCD displays and a membrane (or other type of) keypad. As in the previous case, cumulative totalizing display and batch total displays are common two-line displays for the machine. An accuracy of ±0.25% FSD is available from the control system.

Dispensing in pharmaceutical industries: Loss in weight (LIW) and gain in weight (GIW), which have been discussed in Chapter VIII, are deployed for batching and dispensing systems mainly with powdered pharmaceutical ingredients. Batch size, number of materials, and accuracy requirements, etc. determine the type of batching, (i.e., LIW or GIW, to be deployed). Gravimetric batch blenders dispense material sequentially into a common weighing hopper in the desired proportions. Typical accuracies, which can be expected with the GIW method of batch weighing, are ±0.5% of the full-scale capacity [14]. In LIW measuring is done for the material lost from the feeder, the accuracies expected can be much higher—in the range of 0.1%−0.5% [14].

Apart from these, plastic feeding and dispensing also make use of gravimetric dispensing either in LIW or GIW. Controllers play an important role in flow measurement and its regulation. So, as we now have an idea about batch controlling, we now look into details of the other flow controllers.

7.0.0 FLOW CONTROLLERS

Like any other controller based on applications there will be flow controllers in the process to regulate the flow in the process pipe; for example, when there is demand from the flow control valve in a fuel oil/gas line to regulate the flow to the furnace. Then *what is special about it?* In certain applications there are requirements to ensure constant volume flow, i.e., HVAC applications. There are also some applications where constant mass flow is very much necessary, e.g., gas chromatography and/or other research applications. In this section a brief discussion has been presented on constant volume and constant mass flow controllers. The discussion starts with constant volume flow controllers.

7.1.0 Constant Volume Flow Controllers

As the name signifies the basic issue is to ensure constant flow over the operating range. These are mainly used in gas/air services in HVAC applications. However, there are a few liquid constant volume flow controllers also. These are basically a flow meter with a built-in controller with the meter electronics and an integrated valve with the meter.

7.1.1 CONSTANT VOLUME FLOW CONTROLLER IN GAS APPLICATIONS

Constant volume flow controllers are extensively used in HVAC, both in supply and return lines. The discussions start with their working method.

1. **Working method:** Volume flow rate controllers are mechanical systems and do not require external power for their operation. In constant-volume controllers, flow control is achieved by easy-moving, asymmetrical-angled control blades positioned by aerodynamic forces so that a preset volume flow can be held constant over the entire differential pressure range. An inflatable control bellows amplifies the aerodynamic closing force and acts as an oscillation damper [15]. A leaf spring and cam plate, shown in Fig. XI/7.1.0-1, oppose the closing torque generated due to an aerodynamic closing force. The cam plate is calibrated with respect to differential pressure so that as the pressure difference changes, the angle of the control blade is set so that the volume flow remains constant within close tolerances. However, there can be constant volume flow controllers with actuators also. Control plate balancing is achieved by a vertical counter weight used with a control blade.

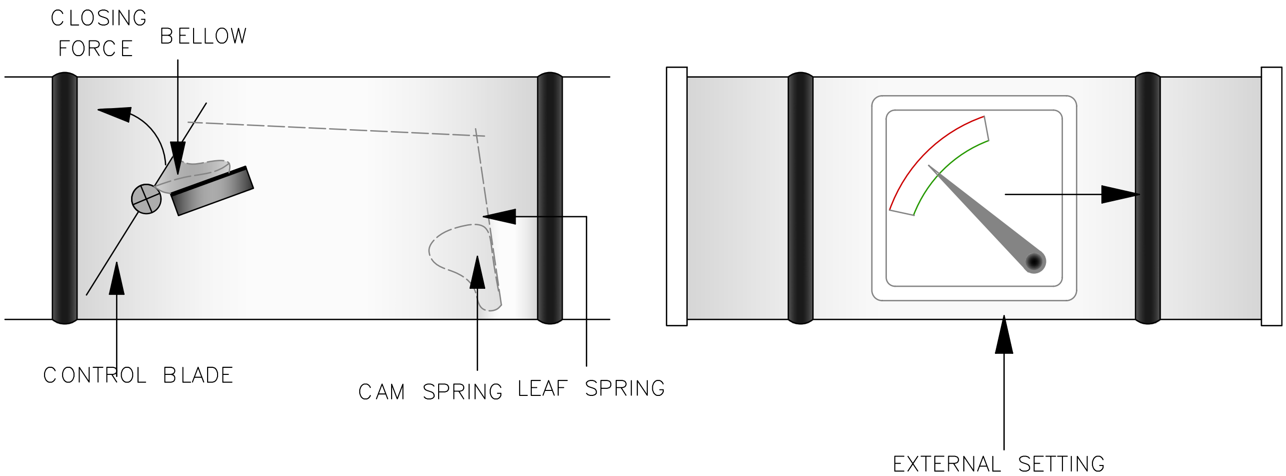


FIGURE XI/7.1.0-1 Mechanical constant volume flow controller.

2. **Temperature range:** Normally these types of controller can easily operate in a temperature range of −25 to 140°C. However, when actuators are used in the controller the temperature range for operation may be narrower.
3. **Setting and precautions:** Normally these are supplied with factory setting/calibration for volume maximum and minimum, corresponding to "OPEN" or "CLOSED," respectively, against associated differential pressure settings. However, it is possible to change the set points volume minimum and maximum at a later stage, even after installation. Such a setting change can be carried out externally, as shown in Fig. XI/7.1.0-1. On account of its style of operation it can also be used as a room or duct pressure regulator. In variable-volume configurations, the volumetric flow controller can regulate variable volumetric flows between the volume minimum and maximum as a function of the supply air (room temperature controller). With the possibility of a high dust concentration, it is recommended to use a filter at the upstream side. These are not suitable for air/gas with oil or sticky materials.
4. **Available characteristics and features:** This type of controller can operate with a low-pressure difference, which is a function of the volume flow, up to a large pressure differential of >1000 Pa. The typical flow rate variation over the entire pressure range is around ±5%. It can also operate with low air velocity. It can be used in any orientations of horizontal/vertical with a turndown of flow at around 5−4:1. These are often used with air heaters and also often offered with acoustic cladding to eliminate noise. They are found in different sizes, from about 80 to 450 mm, to cater to the wide range of volume minimum to maximum with different gas velocities.
5. **Electronic control:** As mentioned earlier, these dampers have better operation and control with actuators. There are controllers available for direct mounting on actuators. These actuators with built-in controllers find their applications in building management for chemical plants, petrochemical plants, and offshore plants to regulate the supply and exhaust air flow. There should be an additional ventilation damper with a built-in orifice and known shield/K factor. These are available with an IP66 enclosure with suitable displays and are available for operation with a supply voltage of 24 VDC. The display unit shows the settings as well as the current status during operation. Sensors and controllers are put in a single housing. These units can be directly mounted on the actuator of the damper. They are available for hazardous applications also and are found in an aluminum enclosure with IP66 rating. These units can accept a number

of analog I/Os. They are programmable units and can be set at site through menu-driven programs. Some of them are available with password protection to prevent tampering.

7.1.2 CONSTANT VOLUME FLOW CONTROLLER IN LIQUID APPLICATIONS

These types are basically liquid flow meters with PI controllers within flow meter electronics and integral valve arrangement. They find their application in dispensing liquid products over a wide range of flow rates. Rapid valve response accommodates changing flow requirements and short dispensing periods. The front display includes the rate flow, totalized flow, batch total, etc. There is an operator interface to set the flow as well as status displays. They are available in various ranges starting from 0.5 CC/mm to >5 lpm, with an accuracy of +2% FSD. The integral valves are normally closed type. These controllers can provide outputs in the form of analog 4–20 mADC, Receive Send (RS) link. They are available in various IP ratings and pressure ratings greater than 10 barg. A typical constant volume flow controller in liquid application is depicted in Fig. XI/7.1.0-2. The instrument type could be thermal type, duly calibrated for volume, as discussed in the next section.

Constant mass flow meters are more popular and frequently used for both gas and liquid services, which are discussed in the next section.

7.2.0 Constant Mass Flow Controllers

As shown in Fig. XI/7.2.0-1, these are constant digital mass flow controllers. They enable extremely precise and long-term stable measurement and control of mass flow over a wide control range of 1000:1. These flow controllers normally have an extremely fast response time.

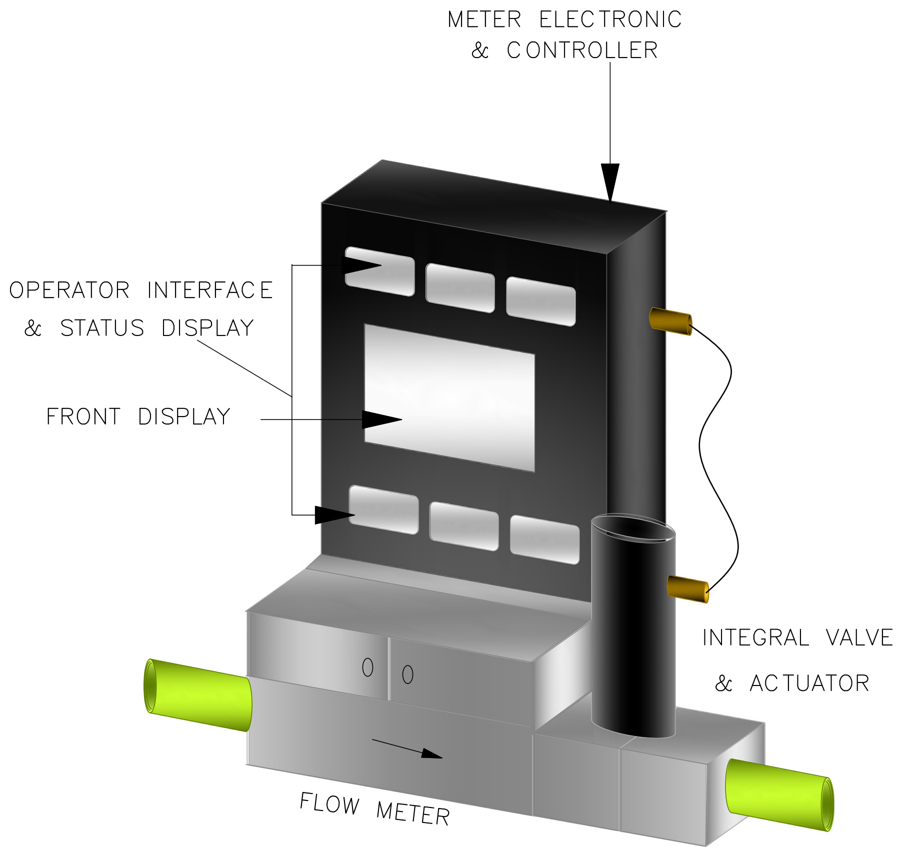


FIGURE XI/7.1.0-2 Constant flow controller for liquid.

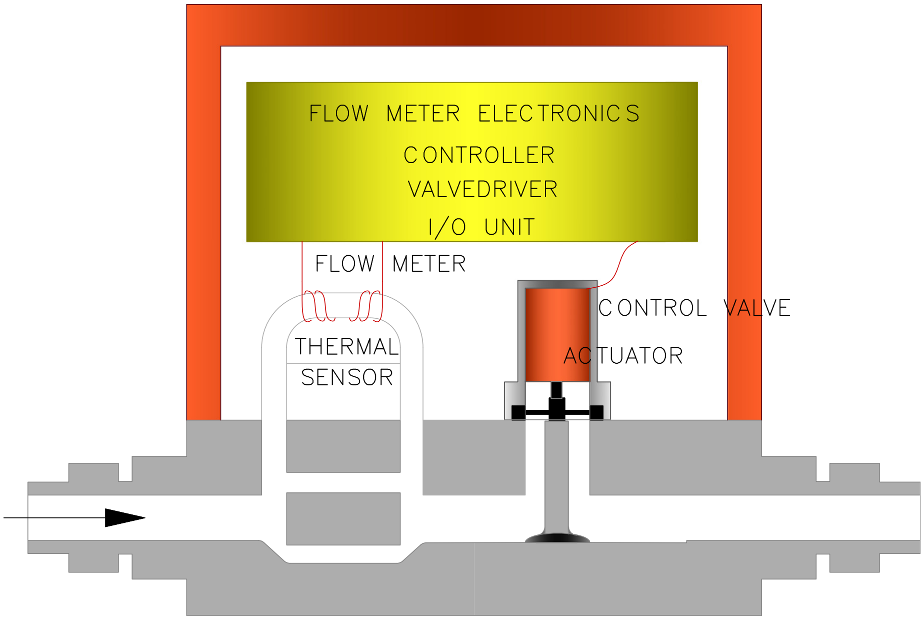


FIGURE XI/7.2.0-1 Constant mass flow controller.

The meters normally offer high accuracy, reliability, and stability.

7.2.1 APPLICATION AREA OF MASS FLOW CONTROLLERS

These types of meters can be used both in liquid and gas. There is a wide application area for liquid and gas mass flow controllers. However, there is high demand for precise gas mass flow controllers in the following:

1. Semiconductor industry;
2. Liquid and gas chromatography applications;
3. Chemical industry;
4. Food and pharmaceutical industry;
5. Analytical laboratories;
6. Organic dye—sensitized.

Before any other discussion we discuss how these operate.

7.2.2 DESCRIPTION OF MASS FLOW CONTROLLERS

The discussions presented below should be read in conjunction with Fig. XI/7.2.0-1. This figure may be compared with Fig. VI/4.1.0-2. Basically both are the same, but here the integral control valve has been depicted. As shown, a proportional amount of flow is bypassed to go past the sensor to measure the total mass flow as discussed in Section 4.1.0 of Chapter VI. Mass flow is computed in an associated processing system. An integral control valve is also connected to the processor. The electronics associated with the flow meter also houses a controller. Based on the set point set at the front panel the flow control valve (made of stainless steel SS 302,316) operates to regulate and ensure the required quantity of fluid passes through the line. These meters support fieldbus for communications, in addition to RS links and analog outputs. Most of these meters have high-quality diagnostics for fault detection. Discussions on flow controllers end here, for specification and other details Section 4.1.0 of Chapter VI may be referenced.

8.0.0 SIGNAL PROCESSING IN SMART TRANSDUCERS AND CONVERTERS

This heading may be little confusing in the sense that basically a transducer is a device which also converts one form of energy to other. Then, *why have the two been indicated separately?* Actually, a transducer represents a device which provides a

usable output (normally electrical output) in response to a specified physical measuring parameter, where a DP transducer converts differential pressure into electronic signal. A simple converter, on the other hand, can convert one type of electrical signal to another type, e.g., a Hall effect or magnetic pick up of a turbine/PD flow meter converts pick up outputs into standard output signal. When talking about smart instruments, basic output portions are basically the same in both cases. Smart transmitters are very popular, and we start the discussion with the smart transducer/transmitter shown in Fig. XI/8.0.0-1. Here, intentionally, the word *transducer* has been used in place of *transmitter* to include signal converters *also*. In order to understand the function of SMART (single module auto-ranging remote transmission) devices one has to remember that the main part of the electronics is basically microprocessor-based circuitry to perform various functions according to the programming. With the advancement of modern electronics these microprocessor-based circuits are actually embedded microcontrollers meant for specific services. In smart transmitters/converters there are two versions available. These are smart transmitters with HART (highway addressable remote transmission system), or with a fieldbus communication. Within fieldbus there are a number of types, the most commonly used types are foundation fieldbus and Profibus. (Details on fieldbus have been covered in Appendix VII in this book.) These variations come from how the transducers have been configured and/or programmed, i.e., not many variations in secondary electronics for smart converters/transmitters (PT/DPT/MVT). It is better to first understand the functions of processors and memory in the secondary electronics:

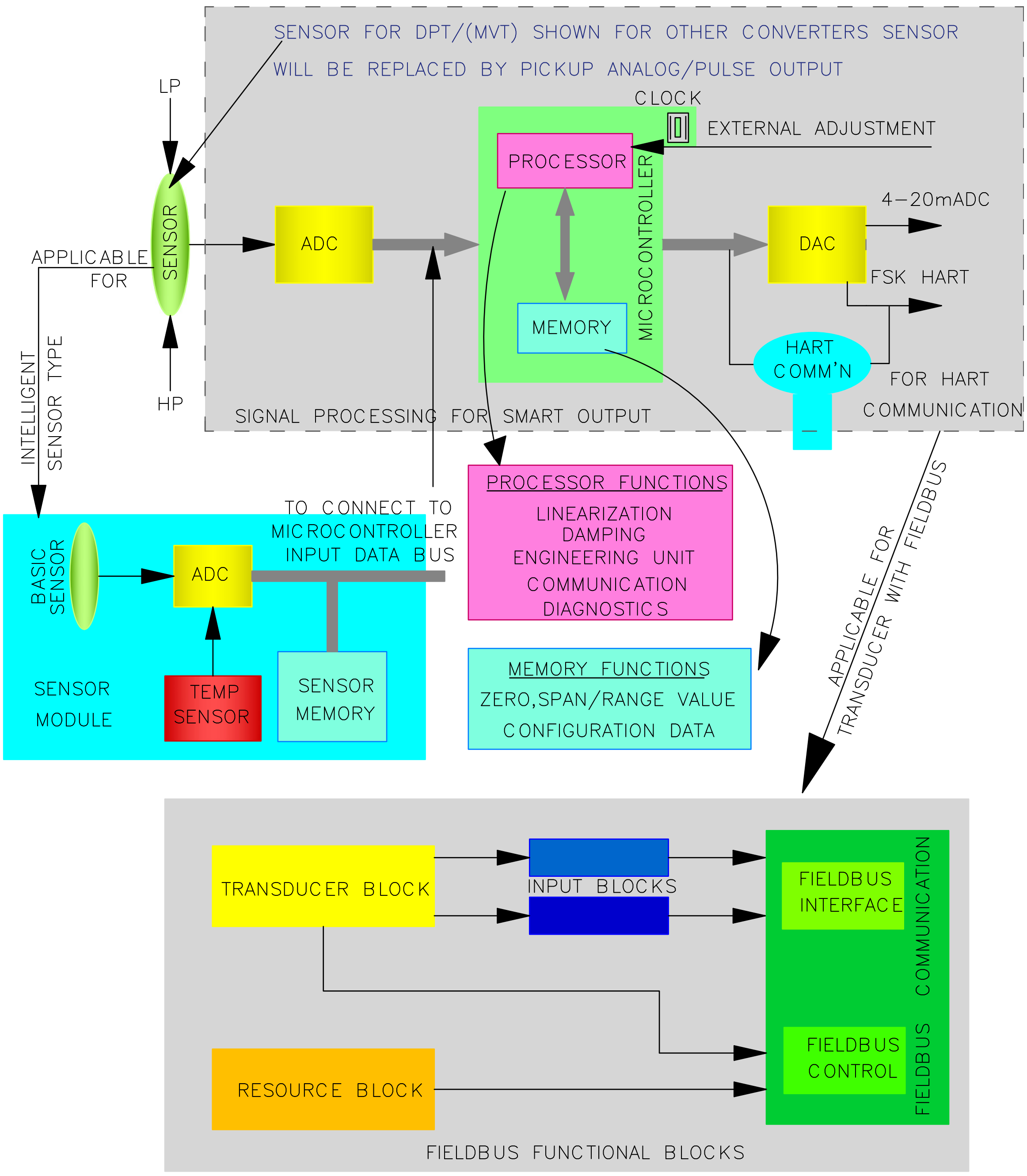
1. **Functions of the processor:** The major functions of processors are:
   - Auto ranging;
   - Linearization (e.g., square root extraction);
   - Damping;
   - Engineering unit;
   - Communication;
   - Diagnostics.
2. **Functions of memory:** The memory function includes but is not limited to:
   - Range/span/zero data;
   - Configuration.

Any changes through the configurator would effectively change the programmed parameter in the transmitter/converter. However, external changes such as hardware change in the system can effectively be done like that in conventional transducers.

In order to understand this the discussion starts with typical differential pressure transmitters with reference to Fig. XI/8.0.0-1.

8.1.0 Standard Transmitters

A standard DPT (without intelligent sensors) is shown in the top part of Fig. XI/8.0.0-1. The sensor (capacitance/reluctance/strain gage/piezoelectric/resonant and any other type) is connected by hardware to the electronics of the transmitter located in the transmitter housing. The electronics consists of a microprocessor with an associated clock, and memory and two peripherals such as an analog-to-digital converter (ADC) and digital-to-analog converter (DAC). ADC is used to take the analog signal to convert it into a digital signal to be transmitted over the data highway shown by the wide lines. Similarly, DAC is necessary to get the analog 4–20 mADC output from the intelligent system which produces a signal in digital form. As stated earlier, transmitters can be used for HART/Profibus/Foundation fieldbus, etc. Therefore, each type there will be factory set so that the end user needs to specify through the ordering code. Since these are microcontroller based systems, PID control algorithms can be developed.



LEGEND

ADC: ANALOG TO DIGITAL CONVERTER

DAC: DIGITAL TO ANALOG CONVERTER

FSK: FREQUENCY SHIFT KEYING

HART: HIWAY ADDRESSABLE REMOTE TRANSMISSION

HP: HIGH PRESSURE

LP: LOW PRESSURE

SMART: SINGLE MODULE AUTO RANGE TRANSMISSION

FIGURE XI/8.0.0-1 Signal processing in smart transducer.

8.1.1 HART TRANSMITTERS

In the case of HART output the intelligence of the electronics has been programmed in such a way that it follows the HART protocol (discussed in Appendix VII of this book) to produce a digital signal output in frequency shift keying (FSK) form. For this reason there are terminals in the transmitter for signal transmission in two-wire mode and include a configurator for testing and configuration purposes as shown in Fig. XI/8.0.0-1.

8.1.2 FIELDBUS TRANSMITTERS

When the transmitter is selected for fieldbus there will be a few functional blocks like transducer block, resource block, etc. during configuring/programming of the transmitter. Such blocks have been clearly shown in the block diagram shown in Fig. XI/8.0.0-1 at the bottom part. There will be a number of input blocks for configuring number of inputs. For device communication details including fieldbus refer (Section 3.0.0) of Appendix VII.

8.1.3 INTELLIGENT SENSING

Most modern transmitters have an intelligent sensing module, i.e., they have intelligence built into the transmitter sensing part. Therefore, the sensor communicates with the secondary electronics over a data highway and ADC is shifted to the sensor module. As necessary there will be temperature sensing for compensation requirements as necessary for the sensors. The memory keeps the characteristic curves of the sensor for ambient variations. Since the sensor is intelligent, communication with secondary electronics are over the data highway as shown in Fig. XI/8.0.0-1.

8.2.0 Smart Converters

In the cases of various other flow meters, like electromagnetic flow meters, turbine flow meters, etc. there will be pickups (see Chapter X) to measure flow. These pickups develop small electrical signals, which are amplified and processed in secondary electronics to produce analog(/pulse) and/or HART or fieldbus communication signal. As indicated above, the smart parts of the electronics for these converters are the same. Only in those cases where the output of the pickups will be connected to the secondary electronics (in some case may after preamplifier stage) in place of sensors is shown. The rest of the explanations and functions of processors and memory are as described in Section 8.1.0 and will also apply for these converters also.

With this, the discussion on flow controllers is concluded. We look into the details of the application of flow in various process and industrial plants as discussed in Chapter XII.

LIST OF ABBREVIATIONS

ABS Absolute
AC Alternating current
ADC Analog-to-digital converter
AI Analog input
AO Analog output
AR Actual reading (in connection with accuracy)
CCW(/CW) Counterclockwise (/clockwise)
CEP Condensate extraction pump
CMRR Common mode rejection ratio
CMV Common mode voltage
COC Change over contact
CPU Condensate polishing unit
CS Carbon steel
CV Calorific value/control valve
DAS Data acquisition system
DC Direct current
DCS Digital control system
DI Ductile iron/digital input
DO Digital output
DP Differential pressure
DPDT Double-pole double-throw
DPT Differential pressure transmitter/transducer
DSP Digital signal processing
EMC Electromagnetic compatibility
EMI Electromagnetic interference
FAT Factory acceptance test
FC Fail to close (for valve)
FO Fail to open (for valve)
FSD Full-scale division (of calibrated span; in connection with accuracy)
HC Hydrocarbon
HVAC Heating, ventilation, and air conditioning
IC Integrated chip/internal combustion (engine)
ID Internal diameter
I/O Input/output
I/P Current to pneumatic converter
IS Intrinsic safety
LCD Liquid crystal display
LDA Laser Doppler anemometry
LDV Laser Doppler velocimetry
LED Light-emitting diode
LHS Left-hand side
LRL Lower range limit
LVM Limit value monitor
MS Mild steel (main steam)
MUX Multiplexer
MVT Multivariable transmitter
NB Nominal bore
NIST National Institute of Standards and Technology
OD Outer diameter
PCD Pitch circle diameter
PLC Programmable logic controller
PT Pressure transmitter or pressure temperature (P/T)
PTFE Polytetrafluoroethylene
PU Processing unit
PVC Polyvinyl chloride
PVT Pressure volume temperature
RF Raised face/radio frequency
RHS Right-hand side
RPM Revolutions per minute
RTD Resistance temperature detector
SG Specific gravity/steam generator
SIL Safety integrity level
SPDT Single-pole double-throw
SPST Single-pole single-throw
SS Stainless steel
STP Standard temperature and pressure (Fig. I/1.1.2-3)
TC Thermocouple
TD Turndown
URL Upper range limit
US Ultrasonic/United States
VDU Visual display unit
VFD Variable-frequency drive
VM Valve manifold
W/O Without/water in oil (emulsion)
WRT With respect to

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CHAPTER XII

FLOW IN PLANT APPLICATIONS

Chapter Outline

PREAMBLE

In previous chapters various technical details, theory of operation, installations, and calibrations, etc. related to plant flow measurement, as well as controls, have been discussed. These discussions mainly cover the theoretical aspects of flow measurements and controls pertinent to different types of devices. The entire focus is put on measurement and control issue from a device point of view. On the other hand, there are many industrial plants and in each of these plants there can be *wide varieties of flow-measuring and control devices*. For example, if we take the case of a thermal power plant there can be various kinds of head type flow measurements alone, e.g., the flow nozzle for main steam flow, orifice plate for condensate flow, Venturi for air flow, Pitot tube for secondary air flow, even the V cone flow for dust-laden air flow/flue gas flow. Naturally, this justifies the statement made above that

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there can be "*wide varieties of flow-measuring and control devices.*" This is not new, because in previous chapters we had seen that based on process conditions and fluid types, flow-measuring devices change and, based on meter selection criteria discussed in Chapter I, flow meters are selected. There are certain specific reasons and problems for which direct measurement of some flows are avoided, e.g., coal flow at a coal mill outlet in a thermal power plant. In certain cases, even if flow measurement is possible, it is avoided, e.g., steam flow measurement in large utility stations ($\geq$500 MW) to avoid energy loss due to pressure drop. These examples show that there are some plant-specific requirements for flow measurements. These aspects will be touched upon in this chapter to complete the discussions on flow measurements and controls. Apart from this, there are certain genuine (problematic) issues for which even after selection of the best flow meter for particular applications there can be problems in flow measurements. These are clear from the following examples (a few only are explained):

- Measurement of flow: of dry ash flow in a power plant, or of a secondary/tertiary air cement plant;
- Measurement issue related to flow measurements of pulp slurry in paper plants;
- Multiphase flow measurement in offshore wells.

Of these problematic issues some of them will be generally common, while some are plant-specific. It is not possible to cover plant types individually so these have been put under different categories:

- Thermal power plant;
- Nuclear plant;
- Oil and gas industries (to cover upstream, midstream, and downstream)
- Papers and chemicals;
- Food, beverage, and pharmaceutical;
- Steel and metal.

There are some common problems normally faced in various plants as well as the types of flow meter used. If one looks at these problems very closely one notices that there are two kinds of problems. The first are the kinds of problems arising out of the process or system, e.g., problems due to dust/corrosion and kinds of problems associated with or typical of flow meter types when used in plants under different situations. There is another kind of situation or problematic issue, i.e., slurry/air bubble, which may be found in most plants and cause problems to most of flow meters. In this section all these common types of issues will be addressed. The discussion starts with an issue commonly encountered in various plants, i.e., flow measurement of gas in dust-laden conditions, etc. This will be followed by some instrument issues and finally will be concluded with another common problem for plants.

1.0.0 GENERAL PLANT ISSUES RELATED TO FLOW MEASUREMENT

In this section a brief discussion related to flow measurement problems commonly encountered in major plants is given; these issues are common and not plant-specific. The impact of flow inaccuracy due to an installation problem and/or dust could happen in any plant. Therefore, these kinds of issues have been segregated and discussed in this section. The discussion starts with measurement issues due to dust.

1.1.0 Issues Related to Industrial Dusts

When a gas is contaminated with dust there are a number of issues which cause and pose problems for its measurement and control. Dust not only creates a problem due to chocking or blocking but if the dust is combustible then there could be explosion problems due to its presence. Also, dust can create pollution health problems. We start the discussion with common problems

associated with dust issues affecting flow measurement. Later discussion has been presented on how flow measurement techniques can be used.

1.1.1 INSTALLATION PROBLEMS AND SOLUTIONS

One of the most common problems associated with dust is the blocking of the impulse line, i.e., blocking of the impulse line for measuring DP in a head type flow meter. This is a common problem with dust for pressure measurement also. In such cases purging is used to remove dust.

Drain: With reference to Fig. II/4.2.3-1 it can be seen that in the case of dirty gas the impulse line has to be taken with an upward slope so that the dust flows down to the duct due to gravity. This is possible when the transmitter is mounted above the tapping point. It may not be possible for cases when the instrument is to be placed below the tapping point on account of layout constraints, as shown in Fig. II/4.2.3-2. In this case a TEE and drain pot are used in the installation so that the instrument is placed above the TEE so that dust can be drained to the drain box. In both these cases purge connection through a cross is also used.

Purging connections: In many cases these are used to prevent plugging, freezing, and corroding. These purge fluids must be compatible (have no interaction with process fluid) with the process fluid. Care should be taken to see that purging does not introduce any error into the system. The quantity of gas/liquid purge has to be regulated. Purge fluids are normally independent of process fluids so that it is available even when the process fluid is not operating. Normally a purging system has a check and shut-off valve. Purging is used for dirty gas flow measurements. In this connection, Figs. II/4.2.3-1 and II/4.2.3-2 may be referenced. As can be seen item 16 is a quick disconnect fitting (for dirty gas) and has been kept in the installation diagram. Through this point the entire line can be purged to remove dust in case of blocking due to dust ingress.

Poking: In certain cases there can be a suitable Y connection near the tapping point to poke the dust or solid formation tends to block the line. This cannot be used everywhere.

The solutions discussed here are mainly applicable for head type flow measurements which actually take the lion's share in flow measurement in gas with dust. However, for other flow meters, like bypass thermal mass flow meter or ultrasonic flow meter this can be deployed also. In the case of bypass thermal flow meters there can be a problem associated with the flow restriction used.

1.1.2 USE OF PURGE ROTAMETERS AND OTHER TYPES

1. **Purge rotameter:** Recall the discussion in Subsection 9.1.4.3 of Chapter II on the purge rotameter. The basic principle lies with maintaining a small flow of inert gas (or water) into the duct containing dirty gas, i.e., slightly positive pressure of inert gas (or water). Such slightly excess air pressure is maintained by the DP regulator shown in Fig. II/9.1.4-1B. When we measure the gas flow we measure DP across the flow element. In the purge method, instead of connecting DP lines directly to the instruments, two lines from the purge meters are connected to the DPT. Each line air pressure is maintained slightly higher (but at a constant amount). A typical measurement scheme is shown in Fig. XII/1.1.0-1.

   When a purge rotameter is used there will be no need for an additional air purge connection for impulse line. In this figure a Venturi is shown but it can be applied to other head type measurements also, such as Pitot tubes and averaging Pitot tubes.
2. **Miscellaneous other methods:** There are a few other ways and means that are also adopted. The special design of the Pitot/average Pitot tube shown in Fig. II/6.2.5-1 may be issued. In such a case the HP tapping is placed along the flow direction. Similarly, a Krel bar, shown Fig. II/6.3.0-1 in chapter II, may be used in gas flow measurement with dust content.

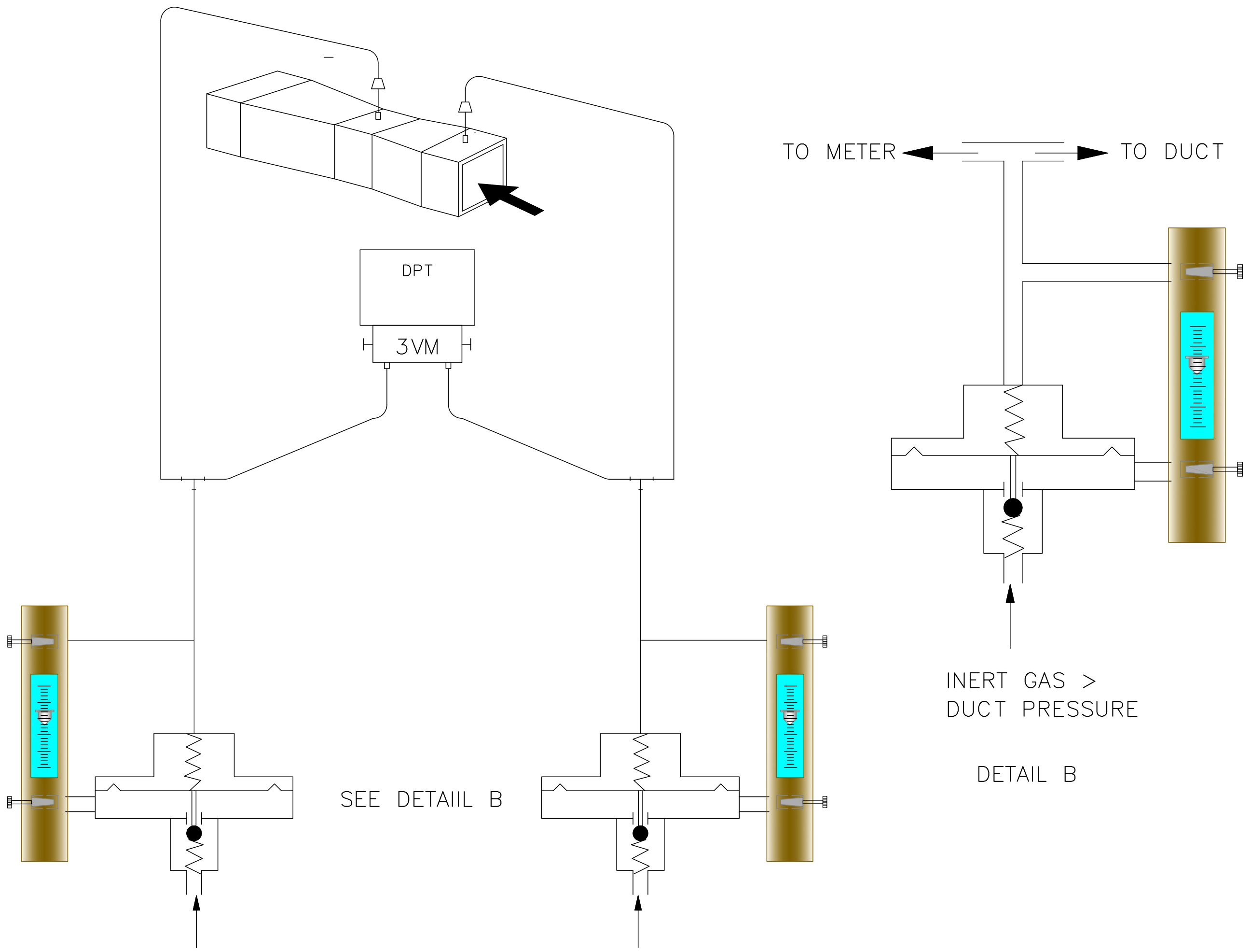

FIGURE XII/1.1.0-1 DP measurement by purge rotameter. Fig. II/4.2.3.2 may be referred to for fitting details. Measurement scheme only, not to scale.

1.1.3 OTHER GAS FLOW METER TYPES

Apart from head type flow meters, thermal flow meters and ultrasonic flow meters also find their applications in the measurement of flow for gas laden with dusts. Factors like those detailed out below should be taken into considerations while selecting the meters type for measurement of flow in gas laden with dusts:

1. Gas temperature;
2. Ambient temperature;
3. Flow meter location;
4. Available flow meter mounting facility;
5. Straight length requirement/available;
6. Amount of particulates in the gas;
7. Chemical composition of the gas;
8. Moisture content.

High levels of particulate in the gas can cause plugging of impulse lines and the meter for head type meters (as already discussed). Similarly, a high level of dust can coat thermal sensors or obstruct the beam in an ultrasonic flow meter. Added to this, if there is a high moisture content, coating formation will be aggravated. Measuring techniques based on thermal principles are widespread. In the simplest of these—the hot-wire anemometer—gas flow is determined via the rate

of cooling of an electrically heated wire with a temperature-dependent resistance. Advanced methods use a heating element and at least two temperature sensors, which measure the transport of heat through the gas. A bypass thermal mass flow meter can be used also, provided coating formation can be avoided. Also, a noninvasive US technique can also be used, provided the dust concentration is not too high.

1.1.4 DUST CLOUD MEASUREMENT

Apart from blocking the impulse lines during flow measurements, dust in industrial plants has very dangerous effects, especially in industrial plants where there is a combustion process. For example, coal dust not only creates measurement problems but also can be dangerous when accumulated in one place and can give rise to an explosion. That is the reason that sealing of a coal mill in a power/cement plant is important. In industrial plants producing combustible dusts or dust-containing goods, which are processed or stored, there is every possibility for explosions. When there are dust/air mixtures with concentrations above the lower explosion limit (LEL) and below the upper explosion limit (UEL), various modes of ignition explosion can always happen [1,2]. For details on LEL and UEL, Ref. [1] may be referenced.

Dust clouds can be described and determined by the following parameters:

- Velocity and local and temporal turbulence intensity;
- Dust distribution: local and temporal dust concentration.

Of these two, velocity measurement is of most importance for this book.

We know that turbulence may be described as a state of rapid, more or less random, movement of the particles of a dust cloud (of concern in the present context) relative to each other in three-dimensional planes. Of the two kinds of turbulences, the initial turbulence is generated by the industrial process in which the dust cloud is formed, whether a cyclone, a pneumatic transport pipe, or a mill. The second kind of turbulence is generated by the explosion itself by expansion-induced flow of unburned dust clouds ahead of the propagating flame front [2]. Laser Doppler anemometry (LDA), discussed in Section 7.3.0 of Chapter V and Subsection 1.2.4.4 of Chapter IX, is commonly used to measure eddy flows in various fields. With this technique and by fast data collection, it is possible to describe the turbulent structure of the flow and to measure the velocity of particles (not of the air flow). Therefore, tracer particles like TiO_2 are often used to make an air flow measurable for the laser Doppler anemometry [2].

1.2.0 Different Flow Meters and Associated Issues

Each flow meter has some pros and cons associated with it. Similarly, there are certain specific problems/issues associated with the meter. In this section some selected issues have been discussed through various literature studies and our own site experiences.

1.2.1 DIAGNOSTIC FEATURES IN ULTRASONIC FLOW METERS

The most prominent feature of the modern ultrasonic flow meter, especially for multipath meters, is its ability to monitor its own health, and to diagnose any problems. Various issues associated with this diagnostic feature of USFM would encompass mainly the following factors.

Auto gain: All multipath USMs have automatic gain control on all receiver channels to generate the same level of ultrasonic signal time after time. Therefore, an increase in gain indicates a weaker signal, which can be caused by a variety of problems, i.e., transducer deterioration and fouling of the transducer ports. However, pressure and flow velocity also affect the signal strength. As long as the transit times are being measured correctly then there will be no impact on the accuracy due to auto gain change. On the other hand, this gain changes help, detecting some failures in advance.

Signal quality: Ultrasonic transducers send multiple pulses across the meter to the opposing paired transducer for updating the output. Ideally all the pulses sent would be received and used. In reality, sometimes the signal is distorted, too weak, or even the received pulse does not fulfill the set criterion, hence electronics would reject the pulse. The level of acceptance (or rejection) for each path is generally considered as a measure of performance, and is often referred to as signal quality [3]. Unless there are other influencing factors as discussed in next section, the meter should operate at full transducer performance until it reaches the highest velocity set. Here the transducer signal becomes more distorted and some of the waveforms will ultimately be eliminated since they don't fit the pulse detection criteria within the specified tolerance [3].

Signal to noise ratio (SNR): Each transducer receives noise from extraneous sources (rather than its opposite transducer). During the interval between receiving pulses, meters monitor the "background" noise, which can be in the same ultrasonic frequency spectrum. Analysis of this SNR can give an indication about the health of the meter also.

1.2.2 FOULING EFFECT ON ULTRASONIC FLOW METERS

High repeatability and natural zero pressure loss combined with extensive diagnostic features (discussed above) available with USFM give it huge appreciation and applications in industries. However, in most cases, meter laboratory calibration differs highly from actual field applications. This is mainly due to the installation effect, corrosion, and fouling. This is the case with all flow meter types. On account of huge diagnostic capabilities, USFM could be treated differently [4]. It may not be possible to completely eliminate the impact of fouling and corrosion, even with many improved designs. When comparing the specifications of different ultrasonic flow meters, most of these will show similar data but in an actual case there will be some differences. Some of the issues related to fouling and corrosion are discussed here.

1. **Meter calibration:** During flow calibration the meter is clean, however after a long operational period the meter might be contaminated. This will definitely affect the calibration, hence the declared uncertainty will be altered.
2. **Installation effect:** Added to the calibration effect discussed, there will be some effect on uncertainty due to the installation effect also and it will increase the uncertainty effect. Therefore, meters with higher sensitivity to the installation effect will be affected more. In this connection Section 1.3.3 of this chapter may be referenced also.
3. **Meter design:** There are a few options available for meter designs as indicated in Fig. XII/1.2.0-1, which shows three design types.
   - *Conventional parallel chord:* In these designs it is possible to measure close to the pipe wall not reflected ones, hence it lacks the interrogation of the pipe wall.
   - *Conventional reflective chord:* This design can measure a built-up triangular design, as shown in Fig. XII/1.2.0-1; the triangle-shaped paths cannot get very close to the wall.
   - *V12 design:* In this configurationas shown in Fig. XII/1.2.0-1 (rightmost) [4]:
     - "There are five horizontal paths and one vertical aligned path.
     - Each path consists of two chords formed into a single V-bounce (in total the meter is equipped with 12 chords, all with a single V shape).
     - The vertical reflecting path is used solely to detect the presence of contamination liquid layers on the bottom of the pipe.
     - All paths are reflecting, whereby four of them use small acoustic mirrors at the opposite side of the pipe."
4. **Fouling and effects:** Fouling can cause build up on the transducer coating inside the pipe wall. The major effects of fouling consist of:
   - Absorption of US signal on account of the layer of fouling on the transducer;

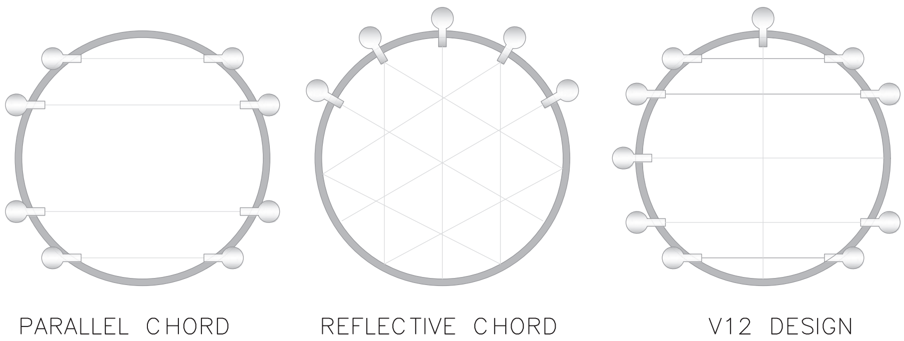

FIGURE XII/1.2.0-1 Ultrasonic meter design variations. *Developed based on J.G. Drenthen, M. Vermeulen, M. Kurth, H. den Hollander, Ultrasonic flow meter diagnostics and the impact of fouling, AGA Operations Conference, Krohne Oil & Gas, 2011. https://cdn.krohne.com/dlc/CONFPAPERS_ALTOSONICV12_impact_of_fouling_en_120524.pdf. Courtesy: Krohne Oil & Gas.*

- Reduction of effective cross-sectional area;
- Higher roughness on the wall;
- Uneven and shorter acoustic path length;
- The attenuation of the acoustic signal through the reduction of the reflection coefficient [3];
- Noise and crosstalk increase in the system.

Reflective design and extensive diagnostics can provide the necessary information on meter degradation in advance through data analysis. For further details Ref. [4] may be referenced.

1.2.3 VORTEX METER AND ASSOCIATED ISSUES

Vortex flow-measuring technology is rather costly technology, applied for various flow measurement applications with the expectation of very accurate measurement. However, there are a few problems associated with the meter. The common natures to the problems and issues associated with the same will be discussed here. One of the most common issues is the proper sizing issue, which the author also faced while using a vortex meter in steam flow measurement in a Rayon factory in Rishra WB India. A few commonly found issues for vortex meters are discussed in this section.

1. **Sizing and selection:** Vortex meter sizing is very important and, as stated in Chapter V, the normal expected flow should be near the middle of the sizing range curve provided by the manufacturer. In many cases, people try to select a meter within the selected meter sizing range curve, with normal being near the minimum detectable flow in the curve. People are happy because the flow range is very much within the range curve. However, in that case the meter may be oversized. This was found by the author in the plant referred to above. It was a retrofit project and the logic behind it was that if a lower size would have been chosen then there would be a requirement for higher straight length. In that case the meter performance was poor on account of oversizing. Therefore, it is recommended that normal flow should always be near the middle of the range curve. For a vortex meter to work, a minimum Reynolds number of 10,000 is essential.
2. **Straight length requirement:** When selecting a lower size meter to meet the requirement discussed above, one must take into account the additional straight length requirement also, which could be nearly 10–15ID for proper vortice formation. In some cases the straight

length requirement may be greater, depending on the obstruction in the line (if necessary flow conditioners may have to be used).

3. **Other issues:** The design of the bluff body and sensor type and location besides the signal strength also play a crucial role in the proper functioning of a vortex meter. The fluid temperature and pressure condition can also be contributory factors for meter performance [5]. However, now, multivariable vortex meters are available where there are built-in RTDs and pressure sensors for calculating mass flow. In this connection Section 3.8.0 of Chapter V may be referenced.

1.2.4 SOME COMMON PHENOMENA AFFECTING FLOW METER PERFORMANCES

There are a number of physical and chemical phenomena which are frequently encountered in industrial plants and cause problems for flow measurements and deteriorate the metering performance. Some of these are listed below, except dust in gas flow measurements, which has been discussed separately above.

1. **Scaling and rusting:** Scaling formation takes place due to the reaction of flowing fluids with metallic pipes. Scales are attached to the inner walls of the piping and attach to the inside of the flow meter to hinder the meter operation. These scales may fragment and break off, resulting in clogging. In the case of electromagnetic flow meter scale formation, this may prevent sensing voltages.

   Rusting is a different phenomenon but has a similar effect.
2. **Sludge:** Abrasive sludge may be formed in a grinding system. Sludge continuously circulates along with the fluid and causes clogging of the flow meter and/or gives rise to noise and interference; naturally performance deteriorates.
3. **Slime:** Microorganisms in water may form slime and disturb the measurements, especially in electromagnetic flow meters.
4. **Slurry:** Details on slurry have been discussed at length in Chapter VII; slurries can obstruct flow and may cause axial wear and clogging.
5. **Bubbles:** Bubbles may come into the flow at intake points, often highly viscous fluids are driven by inert gases. Bubbles cause instability in flow measurement. In the case of a Coriolis meter it may cause imbalance in the meter and it may happen that enough energy may not be available to drive the coil.

1.3.0 Impact of Installation Effect on Meter Performance

Installation of the flow meter is very important as installation has a direct effect on the performance of flow meters in general. A few pertinent cases are discussed here.

1.3.1 PROFILE DISTORTION

Flow meter installation effects in the form of profile distortion normally occur in the following stages:

1. **Development of profile distortion:** The creation and development of velocity profile disturbances are due to the effects of the piping configuration mainly upstream of the flow meter. Disturbed velocity profiles may be asymmetric, contain swirling motions, or have a combination of the two.
2. **Stabilization:** The profile disturbances occur as a result of turbulent diffusion and pipe wall friction. Flow disturbance decay rates may be different but all disturbances require relatively long lengths of straight pipe to reestablish an ideal fully developed, symmetric, swirl-free turbulent velocity profile.
3. **Sensitivity:** Sensitivity to profile distortion varies with flow meter type. When orifice meters are highly sensitive to distortions in velocity profile, USFM has less sensitivity and Coriolis has zero sensitivity towards this. USFMs include computational algorithms that may correct for some amount of flow distortion.

1.3.2 FLOW CONDITIONERS

As seen in Chapter XI, flow conditioners can be used to adjust the flow disturbances with a lower requirement for straight length. Flow straighteners/conditioners field offset the effect of flow field disturbances by greatly reducing the magnitude of the flow distortions. As seen in Chapter XI, some conditioners are effective at “isolating” a fairly broad range of flow distortions. For detailed discussions on this refer to Chapter XI.

1.3.3 INSTALLATION EFFECT ON ULTRASONIC FLOW METER

Multipath meters provide improved resolution of the velocity profile; manufacturers have developed some relatively crude methods to infer swirl and velocity profile asymmetry, thereby reducing (but not eliminating) the sensitivity of this type of meter to changes in the velocity profile [6]. The velocity across the pipe cross-section varies, the velocities associated with each path are taken together to compute an average velocity which is used to calculate the volumetric flow rate. Manufacturers use their standard and proprietary method for average velocity computation.

1.3.4 INSTALLATION EFFECT ON TURBINE FLOW METERS

The indicated volumetric flow rate is determined by dividing the total accumulated pulses by the K-factor. Therefore, if the velocity profile differs from the velocity profile that existed during calibration, it will cause a difference in the number of pulses accumulated during calibration and that in service. Error will therefore be introduced in the volumetric flow rate calculation. Naturally, the distorted velocity profile at the meter inlet will affect the volume flow calculation even if the meter performs well.

1.3.5 INSTALLATION EFFECT ON SECONDARY MEASUREMENT

Secondary measurements are also affected due to installation effects. The accuracy of secondary measurements, like pressure and temperature measurement devices, can be adversely affected by their installations. These installation effects have a direct impact on the accuracy of the temperature element in a thermowell. The temperature of the thermal well can be affected by the pipe wall temperature, when it deviates from the flowing gas temperature and when flow rates are relatively low [6].

1.3.6 DESIGN GUIDELINE REFERENCES

AGA reports provide typical guidelines for installations. Readers should refer to these guidelines from the AGA. Some typical guideline references are listed below:

1. **AGA Report No. 3:** The gas industry standard for orifice meter installations: The revised standard included a recommendation for the minimum length of straight pipe required upstream of an orifice meter for a no-flow conditioner as well as for flow conditioners, e.g., a 19-tube.
2. **AGA Report No. 7:** The gas industry recommended practice for turbine flow measurement. Revised edition 2006. This provides recommended installation practices. It also provides guidance for installing flow conditioners, strainers, filters, and secondary instrumentation.

From the discussions above it transpires that obstructing device(s) upstream distorts the flow profile which will have direct impact on flow measurement accuracy. The persistence of some types of flow disturbances suggests that potential sources of velocity profile distortion further upstream than the immediate meter run should be investigated if piping installation effects are a concern [6]. The effect of velocity profile disturbances on flow measurement accuracy may be different for each meter type. In the case of noninvasive ultrasonic meters, the number of paths and the method of “integrating” the velocity profile impacts the ability of the meter to resolve and recognize distorted velocity profiles. Also, extensive diagnostics of the meter may help early detection of the issue.

We now investigate various plant-specific issues related to flow measurements. The discussions start with the flow issue related to thermal power plants where wide varieties of flow meter types are engaged to measure solid, liquid, gas, and slurry flows.

2.0.0 THERMAL POWER PLANT ISSUES RELATED TO FLOW MEASUREMENT

Of the total energy generated in the world nearly 65% comes from fossil fuel power stations. Naturally, the accuracy of various kinds of flow measurement is of immense importance. In thermal power plants there are a number of flow measurements involved, be it solid (coal), liquid (feed water/oil), or gas (air flow). Steam flow measurement is vital for thermal power plant performance monitoring. Apart from these, there are applications of slurries in ash handling plants and gypsum handling. We start the discussions with steam measurement. This is not only very important in thermal power plant, steam flow measurement is necessary in many process plants also. *Since this is a book meant for flow measurement, it is not possible to detail the intricacy of power plant operations. It is recommended that interested readers refer to the author's "Power Plant Instrumentation and Control Handbook" by Elsevier* [7] *for further details.*

2.1.0 Steam Flow Measurement

It may appear that steam is a straightforward fluid to measure flow. In reality this is not the case, as the measurement parameters vary with the type of steam, as well as with variations in temperature and pressure. Types of steam include wet steam, saturated steam, and superheated steam, when process steam is taken into account. In large utility stations steam flow may be at very high temperature and pressure. Therefore, any technology deployed for steam flow measurement must be able to cope up with condensate handling. Turbine flow meters and Coriolis meters are not good at handling condensate. Ultrasonic meters measure the speed of ultrasonic waves in the medium. The speed with which an ultrasonic wave travels through a metal pipe may be different to the speed of the wave through steam, hence calculation of the flow rate may be affected by interference. On account of this, the head type of meters with different flow elements and vortex flow meters are mostly used. Each of these has some advantages and disadvantages. The vortex has a relatively lower pressure drop and lower straight length requirement, but it is quite costly and sizing is very critical. For large utility stations, very high pressure/temperature may also pose problems. DP meters on the other hand are inexpensive and can be verified easily. Installation of DP type meters is straight forward. Also, process pressure/temperature compensation is easier to implement. In thermal power plants the following are major steam flow measurement points:

1. Main steam flow;
2. Cold reheat steam flow;
3. Auxiliary steam flow;
4. Extraction steam;
5. PRDS steam flow (for process cum power application).

Apart from the vortex meter, flow nozzle and orifice plates are used as DP meter flow elements and can be used for measurement of steam as listed above with the ***exception*** of main steam flow measurement, which has been treated separately in Section 2.1.1. Measurement techniques in both types (vortex meters and DP meters) have already been discussed and hence are not repeated here. In the case of low-pressure applications the orifice plate may be used, otherwise, for high-pressure applications, flow nozzles are used. We now discuss main steam (MS) flow measurement.

2.1.1 MAIN STEAM FLOW MEASUREMENT

Main steam pressure can be measured by DP meters (using a flow element) or vortex meters

(if temperature permits). At large units, especially in supercritical/ultrasupercritical units, very high temperatures can be withstood by the vortex at that high steam pressure. Therefore, the flow nozzle is the only choice. As stated earlier, on account of higher permanent pressure loss (PPL) often in large power plants (>500 MW) direct MS steam flow measurement by nozzles is avoided. Instead, MS flow measurement is substituted by flow computations. In order to understand this it is required to understand the process. The main steam flow basically represents the load (like current in an electrical circuit) delivered by the steam generator (SG) at its operating main steam pressure. MS flow measurement alternatives are listed below.

1. **MS flow by flow nozzle:** Let us understand the measurement with reference to Fig. XII/2.1.0-1A.

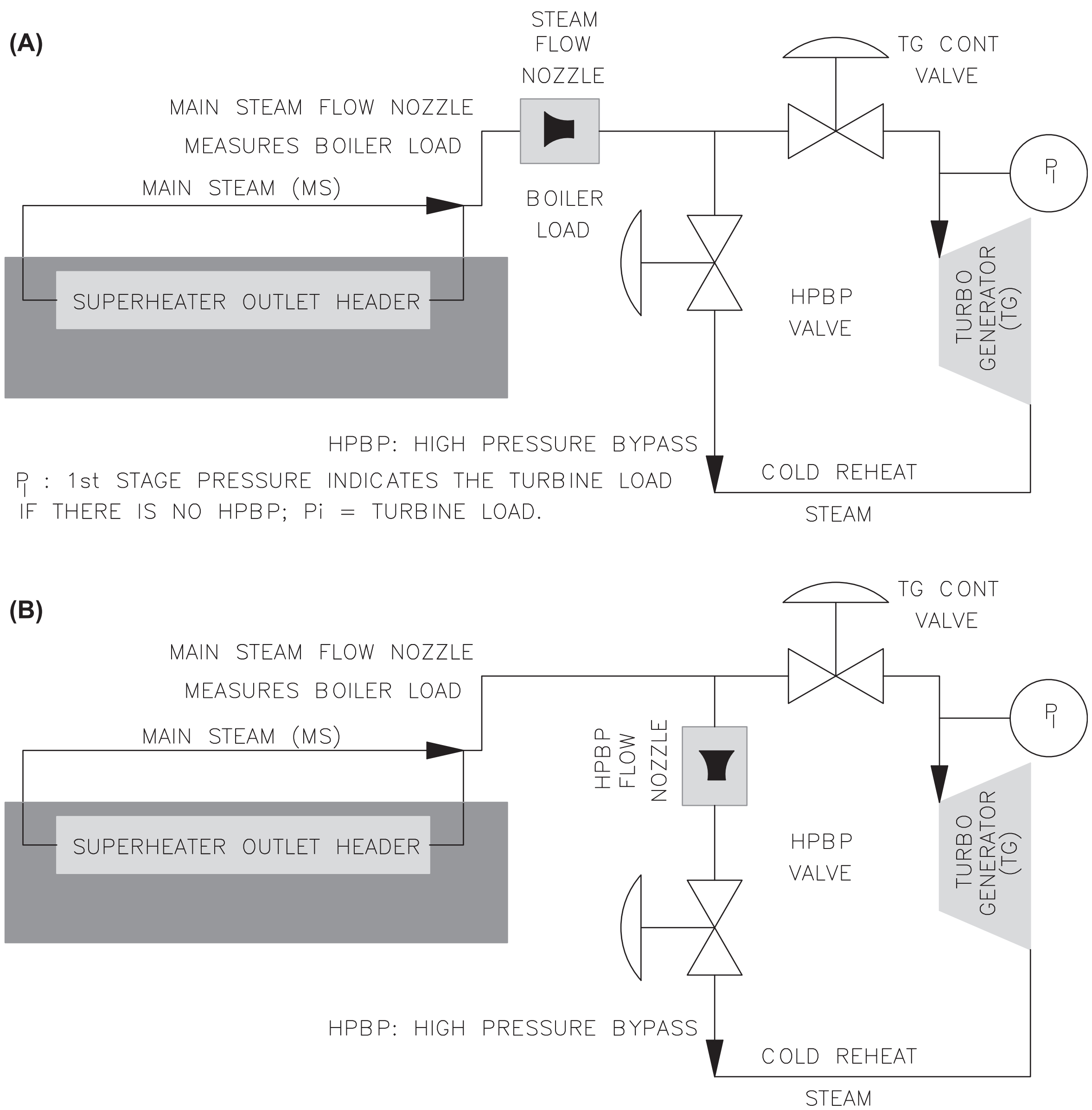

FIGURE XII/2.1.0-1 Main steam flow measurement. (A) MS flow measurement with flow nozzle. (B) MS flow measurement without flow nozzle. Boiler load = first pressure (turbine load) + HPBP load.

MS flow nozzles measure the total steam flow (load) generated by a steam generator (SG). In the case of a boiler of smaller size (in MW), the quantity of flow output will be lower as well as the MS pressure being lower. Naturally, PPL due to the flow nozzle will be lower. PPL time flow gives the total loss due to the flow nozzle. Therefore, if in a larger unit (>500 MW), MS flow nozzles are used, then large flow times PPL (higher) due to the flow nozzle will be quite high. Hence, for larger plants (>500 MW, especially for supercritical/ultrasupercritical units) flow measurement using a flow nozzle is avoided. Fig. XII/2.1.0-1A is mainly applicable for lower MW boilers, up to size <500 MW. This is a general norm stated here. For further details Ref. [7] may be referenced.

2. **MS flow without a flow nozzle:** The MS flow or boiler load can also be measured without a flow nozzle in an MS line as shown in Fig. XII/2.1.0-1B. In the case of the SG/Turbo generator (TG) configuration without high-pressure bypass (HPBP—for details refer to Ref. [7]) or when bypass is not in operation, the total load of the boiler is proportional to the turbine load, i.e., the first-stage pressure steam pressure of TG (say P1). This is the case for both fixed pressure and sliding pressure (normally between 60% and 80% TG load when turbine control valve is in wide open condition, then 1st stage pressue and turbine inlet pressure is same hence can be used) modes of turbine (elaborated in Ref. [7]). When bypass comes into operation, a part of the steam load from SG goes to HPBP so the total load of the boiler is measured as HPBP flow (measured by flow nozzle shown) and first-- stage pressure of the turbine, i.e., boiler steam flow = HPBP steam flow + K. P_I. Here K is constant of proportionality.

2.1.2 OTHER STEAM FLOW MEASUREMENTS

Depending on the process pressure, a flow nozzle/orifice can be used as flow elements to measure steam flow with DP meters at measuring points listed in Subsections 2.1.0.2 through 2.1.0.5. If the temperature and cost permit in those cases vortex flow meters could also be deployed.

It is worth noting that steam flow measurements discussed here (in connection with thermal power plants) are also applicable for all other process plants. Coal flow, which we investigate next, is another critical measurement in fossil fuel power plants.

2.2.0 Pulverized Coal Flow Measurement

Globally, coal-fired power plants generate about 40% of the total electrical power. In coal-fired stations coal is pulverized to feed the same to the boiler for steam generation. Therefore, it is of utmost importance to measure pulverized coal flow to the boiler through various burners. It is equally important to balance the pulverized coal flow in a number of burners which could count over 50 in some cases. It is puzzling to note that a well-established method for measurement of pulverized coal flow to boilers was not available until recently. Nowadays some methods are available but most of are for displays and monitoring. However, these systems also ensure that the operator can also know the distribution pattern of pulverized coal in each burner pipe. This helps in balancing the coal flow in each burner. Such balancing is extremely important for optimizing combustion and maximizing the combustion efficiency in the boiler. There are some sampling methods, as in ASME. As per ASME PTC 4.2, measurement is carried out by sampling particulate flow carried within an air stream. By isokinetically extracting the sample, the particulate flow rate can be determined. The sampling probe features a single, slotted nozzle meeting the geometry specifications of the ASME method. The probe is inserted into a pipe and positioned at different radial positions over the duration of the test. The particulate extraction is via a vacuum system with the extraction rate set by the operator based on the known average air velocity within the pipe [8]. This takes time and is

not a real-time measurement. We now look into this issue in detail and find various methods to infer and measure pulverized coal flow for combustion optimization.

2.2.1 MEASUREMENT REQUIREMENTS AND DIFFICULTIES

In coal-fired power plants the coal is pulverized in a mill or pulverizer and mixed with primary air to pneumatically conveying the coal/air mixture to the varied numbers of burners of different diameters. Accurate measurement of pulverized coal (PF) flow and balancing it in various active burners is absolutely necessary for maximizing combustion efficiency and improved dynamic response to load changes. Also, this helps in reducing the carbon content of the ash, unburnt carbon deposition, or unburnt carbon in fly ash, and reducing greenhouse gases and other emissions.

Coal-flow transport behavior and distribution to boiler burners are not easy tasks and until recently, it proved difficult to meter [9]. Added to this, the dynamics of coal flow are very much dependent on particle size, the physical plant layout, etc. Therefore, on account of the nonavailability of an accurate method of measurement, the realization of pulverized fuel measurement at the boiler could not be done. Also, for precise fuel supply, the mill-control system has to control the primary air flow in a certain ratio to the PF flow, thereby maintaining the efficiency of unit energy release and absorption and so reducing environment emissions [10]. Recently such difficulties have been addressed by a few suppliers coming up with measurement methods.

2.2.2 CONVENTIONAL COAL FLOW MEASUREMENT AND CONTROLS

Coal is fed to pulverizers, where coal is pulverized into fine particles and conveyed to the burner. Prior to leaving the mill/pulverizer it passes through a classifier to ensure only fine (fineness: no less than 72% passing through a 200 mesh screen with a maximum 1% remaining in a 50 mesh screen—ASME data) particles are allowed, so as to have spontaneous ignition at the furnace. There are two kinds of mill: ball or bowl mill and tube and ball mill. In both cases, primary air (PA) is used to drive the coal out of the mill to the burner. A mixture of hot and cold PA is used to maintain the mill temperature within a safe limit and to dry the coal at the same time. There are two different ways coal flow are measured and accounted for.

1. **Ball/bowl mill coal flow:** The ball/bowl mill has a smaller bed thickness, i.e., it has a low milling volume capacity. If the mill trips, associated burners will be cut off from the coal supply. Since the ball and bowl mill does not have enough capacity, the feeder speed, which is varied as per PA flow, can be taken as an approximation of coal feed to the boiler.
2. **Tube and ball mill coal flow:** The tube and ball mill maintains a pulverized coal level. This kind of mill has a higher capacity than a ball/bowl mill. The tube and ball mill has a higher capacity and maintains a level of pulverized coal. One mill/pulverizer can normally cater to two elevations in the tangential tilt furnace and can run the associated burners (boiler elevation) for a certain amount of time even after tripping of the mill. Therefore, the feeder speed cannot be taken as a measure of coal flow. In these mills the damper position of the controlling damper for PA flow through the mill can be taken as a proportional signal to coal flow.
3. **Problem with direct coal flow measurement:** In other applications, such as in blast furnace coal injection or cement plant coal firing, there will be an intermediate reservoir of pulverized coal. For example, in a cement plant, pulverized fuel is stored in a silo for subsequent feeding to the kiln burner and pulverized coal flow can be measured by the feeder and any other means, e.g., the microwave method. In the case of a power plant this is not the case and the power plant is a continuous process and the pulverizer is

directly connected to the boiler—meaning it is an interconnected dynamic system. This causes major difficulties in direct measurement of pulverized coal in thermal power stations. Nowadays there are some solutions.

For details on coal flow control refer to Ref. [7].

2.2.3 PULVERIZED COAL FLOW MEASUREMENT

Electric charge type: Electrical charging of the conveyed solids, due to frictional contact and charge transfer from one to another, is a common phenomenon in solids conveyed pneumatically (Refer Section 7.7.2 of Chapter X also). An electrical sensor set comprising two nonintrusive detection rings is used to detect the magnitude of electrostatic energy, or charge present in airborne particles. During the passage of charged particles, variations in the level of the charge signal on the sensor can be used as an indication of the solids concentration [11]. This is not an absolute measure of solids concentration or mass flow rate since the charge level depends on many factors, such as the chemical composition of the solids, the particle size distribution, moisture content, etc., and these effects are not insignificant [12]. Therefore, in this method relative differences between pipes with the same coal can be compared/displayed. The charged signals mentioned above are amplified and sent to the main processor for analysis. The system processor analyses the magnitude for each sensor and correlates the charge detected by each sensor ring. As the magnitude is proportional to the amount of electrostatic charge within the sensor, the correlation time between two signals over a known distance allows the absolute velocity of particulates to be calculated. As indicated above, the relative fuel flow distribution across a given number, bank, or mill set of sensors is calculated from the proportion of total charge inherent in each sensor [13]. When coupled with the feeding system, the processor can convert relative distribution into an absolute mass flow over a given number of sensors. The PF meters, manufactured by ABB are based on the above principle (trademarked PfMaster) [11]. These sensors are nonintrusive systems and are customized to the pipe diameter and have a circular shape. This instrument takes the form of a spool piece that replaces a section of PF pipe, as shown in Fig. XII/2.2.0-1, to be delivered to the site (after factory testing) for direct fitting.

This type has been developed by ABB Automation, in association with Teeside University, UK. There are other types also. Some of the features are listed here:

- Safe, nonhazardous operation;
- Nonintrusive, passive system;
- Available in various bus systems;
- Customized sizes as spool piece.

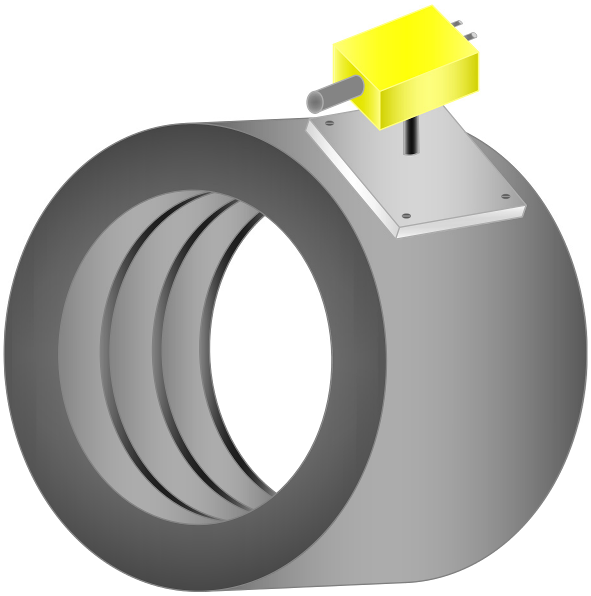

FIGURE XII/2.2.0-1 Electric charge PF flow measurement. Electrostatic detection in each burner coal pipe available in various pipe sizes. *Developed based on Pulverised Fuel Flow Meter, PfMaster, Data Sheet SS/PFMAS_2, ABB Limited. https://library.e.abb.com/public/a2d6b9b461450 85bc1257106003c5d36/SS_PFMAS_2.pdf. Courtesy: ABB Limited.*

Microwave and cross-correlation: There are also microwave types of flow meters. These instruments measure fuel mass flow by measuring the components of coal velocity and density. Microwave-based technology is used to measure coal density (concentration) with the help of low-power, low-frequency microwaves, with each coal pipe functioning as its own unique wave guide. The cross-correlation method is used to determine the velocity of coal fuel and a processor is used to determine the mass flow. Examples of some of these coal flow measurement types are: PROMECON' MECONTROL coal or Green bank's PF Master [13].

There are also other types, such as the acoustic method coal flow monitor (CFM). We now look at air flow measurements.

2.3.0 Air and Flue Gas Flow Measurement

Air and flue gas are extremely important for fossil fuel power station operation. Prior to discussing these we look into the issues of flow measurements in air and flue gas. On account of the heavy dust concentration, direct flue gas measurement is avoided. We now look into the various flow-measuring points in air and flue gas.

2.3.1 AIR FLUE GAS FLOW MEASUREMENTS

Short details of these measuring points, along with measuring methods, are presented in Table XII/2.3.0-1.

Common major issues related to measurement in air and flue gas flow measurements are described here:

1. **Straight length and accuracy:** Air ducts are large, especially for large utility stations, and accordingly straight length requirements for the flow elements mentioned above would be large and may be difficult to maintain in reality. Alternative methods need to be used.
2. **Low DP:** In most cases the DP range for DPTs needs to be very low, hence highly accurate and low DP/Multivariable transmitters are essential.
3. **Contamination:** On account of air heater leakage, especially for regenerative air heaters, there may be the possibility of duct

TABLE XII/2.3.0-1 Measuring Point in Air and Gas Flow Measuring Points

Measurement	Measuring Point	Measuring Method[a]	Purpose
Secondary air flow	FD fan suction/wind box	Piezometric ring, Aerofoil, Venturi	Maintenance of stoichiometric fuel/air ratios
Primary air flow	PA flow to individual coal mill and/or PA flow suction/DP across PA fan	Picolo/Pitot tube	For fuel flow control to boiler
Secondary air flow to individual burner positions	Secondary air dampers control (SADC) in wind box	As per SADC scheme	Air distribution for burners and NO_x control
Over fire air flow	Boiler top elevations	Derived from damper position	NO_x control
Flue gas recirculation	–	Damper position/fan speed inferential	Same as[a] above
Flue gas flow		Inferential	SCR control of NO_x

[a]*Commonly used method; Pitot tube may be replaced by average Pitot tube also.*

contamination. Accordingly, the possible problems discussed in Section 1.1.0 may occur and accordingly necessary measures suggested there need to be taken into account during installation.

2.3.2 MILL AIR FLOW MEASUREMENTS AND CONTROL

One of the critical control loops in the automatic boiler control system is the primary air control system to the mill. The boiler's steam production efficiency is controlled by precise flow regulation of blended primary cold air (CA) and primary hot air (HA), which flow from separate ducts. Both CA and HA are blended together to enter the pulverizer to drive pulverized fuel (PF) to the boiler. The duct air flow is controlled by louvered dampers located inside the ducts.

The criticality of this loop comes from the fact that as the boiler load fluctuates there has to be adjustment of total PA to the mill to ensure required PF to the boiler. This will call for changing the flow of both HA and CA, i.e., both dampers simultaneously need to be adjusted as used to be the case previously. It should be remembered that there is another criterion to maintain the temperature of pulverized outlet temperature which should be kept within a specified range because, if the temperature is on the lower side, dampness in the coal will deteriorate the flowability of PF, on the other hand, if the temperature is too high it will endanger the safety of the mill from fire. So, if both the dampers are adjusted simultaneously there will be the possibility of a severe fluctuation in the mill outlet temperature especially, on cold or humid days, the flowability of PF. Instead nowadays the PA flow demand for the mill, first changes the HA and, based on outlet temperature, the CA is adjusted for finer adjustments. This is so in most cases, especially on cold days, and on humid days the chances of the mill temperature going too high will be less. Even with this arrangement, if there is any change in CA it will affect HA also. From this it is needless to say that accurate, responsive, and reliable air flow measurement is critical to damper control and to the efficiency of the boiler. As stated in the previous section, measurement of air flow with DP type instruments may have some inherent (blocking) problems as discussed above. So, in addition to a Pitot tube or average Pitot tube, thermal mass flow meters/bypass mass flow meters also find applications there. A point worth noting here is that because of the large cross-sectional area of the air ducts and the temperature stratification in the primary air duct caused by the mixing of the preheated and ambient air, more than one thermal mass flow meter may be needed. In this connection, the case study by Fluid Component Internationals LLC [14] may be referenced.

2.4.0 Flow Meters for Abrasive Fluid Handling in a Flue Gas Desulfurization Plant

As per the Clean Air Act, there are currently several restrictions imposed by pollution control boards. As a result of this most plants are equipped with flue gas desulfurization (FGD) plants. In this section a few issues related to FGD are discussed.

1. **Challenges from slurry:** Limestone and gypsum slurries are very abrasive. However, it is necessary to measure these slurries, especially gypsum slurry, in their sludge dewatering process. The measurement is critical for plant operations.
2. **Electromagnetic flow meter:** Commonly used flow meters for these applications are electromagnetic flow meters. On account of the abrasiveness of the slurry, conventional-style PTFE-lined magnetic flow meters used in such applications normally have a short life expectancy. Retained type liners are a better choice, because nonretained liners and electrodes that expose their seal to the process fluid/slurry make the meters prone to fail. Also, if electrodes are of the noninvasive type, the electrode will give raise the slurry noise on account of the collision of solids with the electrode. Also, in such cases high velocity can cause wear on the liner.

3. **Sonar:** The application of a sonar array could be a good solution. These are noninvasive and mounted on the outside of gypsum dewatering pipes. Sonar is not affected by the fibers of FRP pipes like USFM. They are prone to wear.

We now look for flow-metering applications for nuclear power plants.

3.0.0 SOME FLOW MEASUREMENT ISSUES FOR NUCLEAR POWER PLANTS

In a nuclear power plant, water circuits are heated up by nuclear fission of the radioactive material. Most modern reactor types employ primary and secondary cooling circuits, whereas the secondary circuit is used to steam power turbines for electricity generation. On account of the partially abrasive nature of the flowing medium and the chances of radiation, conventional instruments at times are not suitable for nuclear plants. In-line flow-metering technologies furthermore require complete plant shutdowns for their installation or replacement. Nonintrusive flow meters with good accuracy are often preferred. Also, radiation-resistant variants are approved for major nuclear power plants. In almost all cases in nuclear installations only those instruments which are specifically approved for nuclear installations are allowed. Ultrasonic and thermal mass flow-measuring flow meters find extensive use in nuclear power plants. The auxiliary feed water system in nuclear power plants is a safety-related system that maintains an inventory in the secondary side of the steam generators to ensure a heat sink for the removal of reactor decay heat. In these lines, the orifice plate and DP meters find their applications. For contaminated air flow, leak rate monitoring is carried out by thermal flow meters.

In this section short discussions are presented on nuclear flow-related issues.

3.1.0 ASME Code

For nuclear power plants ASME O&M codes are important.

According to the ASME O&M code (Appendix V): (ISTB B &C), nuclear power plants must periodically conduct tests on pumps to ensure the pumps meet regulatory criteria. The ASME O&M code also states that flow rate performance must be within a specific range of pump design. Pump flow rate instrumentation (flow meters) must have a stated accuracy of $\pm 2\%$.

The ASME Code also provides a classification as listed below.

- **Code Class 1:** reactor coolant system (RCS) pressure boundary;
- **Code Class 2:** components in systems connected to RCS;
- **Code Class 3:** systems that affect the function of the RCS (e.g., auxiliary feed water, radioactive waste).

3.2.0 Reactor Coolant Systems Flow Measurement

The accuracy of reactor coolant systems (RCSs) is of immense importance to get the maximum allowable operating power. Direct measurement of flow in large diameter is difficult, therefore, indirect measurement, though not very accurate, has often been deployed for this purpose. Normally the following methods are possible:

- Reactor coolant pump differential pressure;
- RCS elbow tap DP;
- Precise calorific heat balance (PCHB).

3.2.1 ELBOW AND PCHB FOR FLOW

Of these two elbow taps, DP and precise calorific heat balance (PCHB) are mostly used. The elbow tap DP method discussed in Chapter II is used. Flow measurement and reference design are used to determine the proportional coefficient. Affected factors are the inner diameter and radius of curvature.

PCHB flow measurement is performed to provide the reference values for normalization of the elbow tap transmitters. In PCHB, the cold and hot leg temperatures of each loop and thermal power of the corresponding steam generator are measured and the RCS flow rate is calculated by considering the heat balance between the RCS and the secondary system.

3.2.2 DESIGN ISSUES

The various design considerations include mainly the following:

1. **Best flow estimate (BFE):** This is the most likely value for actual plant operating condition. It is based on the best estimated for the reactor vessel, steam generator, and piping flow resistance and the best estimate of the reactor pump head flow capacity. Best flow estimate is used for calculating the fuel assembly pressure drop and the lift force on the operating condition.
2. **Thermal design flow (TDF):** It stands to signify the reactor core thermal performance, steam generator thermal performance, and normal plant parameter used in the design. TDF also indicates the uncertainty in reactor vessel, steam generator, and piping flow resistance, RCP head to measure the flow rate. TDF is used both for conventional thermal design as well as for loss of coolant accidents (LOCAs).
3. **Mechanical design flow (MDF):** This is the high flow used in design and is very conservatively considered. It is the reduced system resistance on increased pump head capability. The intersection of flow resistance with higher pump curve establishes the MDF.
4. **Minimum measured flow (MMF):** This is the minimum predicted flow range expected during flow measurement and used in reactor core analysis.

This is an elaborate system and beyond the scope of this book. Standard nuclear plant design may be consulted.

3.3.0 Sonar in Nuclear Application

A sonar array-based processing system discussed earlier is a nonultrasonic flow meter that uses technology to provide a highly repeatable and stable flow rate measurement. This system offers good repeatability and a specific set of calibration coefficients for this particular application at the plant. These calibration coefficients were then validated on all sensor bands to ensure the reported flow rate accuracy is within $\pm 2\%$ as per the ASME code. These metering systems also offer fieldbus systems for communication. In nuclear plant varieties of flow meters are used Vortex, Fluidic meters, DP type, USFM are a few examples on the various types of flow meters used in nuclear plant applications. With this idea and discussions application of flow meters in nuclear power plant comes to an end to limit the volume of the book.

We now investigate flow-measuring issues related to oil and gas areas.

4.0.0 OIL AND GAS APPLICATIONS

Apart from normal process flow applications, on account of fiscal/custody transfer and dispensing functions, the use of flow meters in oil and gas areas is very large. Similarly, many types of flow meters are used in oil and gas areas. Also, there are multiphase meters in well head measurements. However, there are certain characteristics in oil and gas flow measurement for which all fluid meters cannot be used for this, i.e., on account of their low conductivity, electromagnetic flow meters do not find much applications in oil and gas flow measurement. Also, in many cases, such as custody transfer and fiscal/billing purposes, accuracy and reliability are very important. Safety is also a big issue in oil and gas. Therefore, it is better to get some idea about the various types of flow meters deployed for oil and gas.

4.1.0 Instruments Used in Oil and Gas Flow Measurements

Petroleum oil and natural gas (a mixture of hydrocarbons) are two major natural sources of energy extensively used globally. After they are separated, in single phase they are measured by various flow instrument types.

4.1.1 DIFFERENT MAJOR FLOW INSTRUMENTS USED IN OIL AND GAS

The pros and cons of these instruments' measurements are listed in Table XII/4.1.0-1 for the reader to compare their features and reasons for their usage with their advantages and limitations.

Two instrument types, the wedge flow meter and USFM, need special mention for their use in dirty and highly viscous fluid (wedge meter) and liquefied natural gas (LNG). It is important to use instruments in different stages of the oil and gas process.

TABLE XII/4.1.0-1 Pros and Cons of Different Meters in Oil and Gas Applications

Meter Type	Oil	Natural Gas
Coriolis mass	***Advantages*** Direct mass measurement and density/volume measurement High accuracy repeatability and long-term stability Profile distortion and straight length requirement is not there Used for custody transfer Because of density, better suited in oil ***Limitations*** >100 mm size cost becomes too high >150 mm size limited availability Becomes too heavy and long (especially bent tube types) with increase in size (>150)	
DP types	Established method for custody transfer Dual chamber possible for inspection Higher pressure loss Slowly replaced by USFM	Used for custody transfer Used for stack gas monitoring Higher pressure loss Getting replaced by USFM [22]
PD types	Sample volume to calculate total Positive volume measurement with high accuracy and reliability Wide range of types available Custody transfer application Extensively used for metering in distribution lines, truck/tanker loading/dispensing Competition from turbine meters and now from mass flow meters	Sample volume to calculate total Positive volume measurement with high accuracy and reliability Wide range of types available Well suited for low flow <250 mm Extensively used for gas metering in domestic, commercial, and industrial use Competition from turbine meters and now from mass flow meters
Thermal mass	–	Extensively used especially for multipoint measurement in large stacks Approved measurement by EPA (also for greenhouse gas) [22] Both constant temperature and constant power types are used
Turbine type	Widely used for oil measurement especially with low-viscosity clean fluid With improved design now life expectancy is quite good Available in bidirectional use and improved pressure loss At times competing with DP meters, definitely over USFM	Used for custody transfer Used for fiscal metering in domestic, commercial, and industrial usages Available insertion type and better suited than PD meter in line size >250 mm Facing competition from USFM
Ultrasonic type	Nonintrusive and noninvasive Extensive diagnostic capability Multipoint transit time gives high accuracy In-line types used for crude oil also Approved for custody transfer Cost is only limitation	Nonintrusive and noninvasive Extensive diagnostic capability Multipoint transit time gives high accuracy In-line version is better choice for its accuracy than clamp-on type Insertion type in stack gas monitoring but facing completion from DP/thermal types for cost Approved for custody transfer Cost is only limitation
Vortex type	Suited for LNG measurement Got API approval for custody transfer yet to penetrate the market	Suitable for instantaneous flow measurement They may need flow straighteners Medium accuracy

4.1.2 USE OF INSTRUMENTS AT DIFFERENT STAGES IN THE OIL AND GAS PROCESS

Oil and gas systems can be divided into three sections, i.e., upstream: exploration and production; midstream: transportation system; and downstream: refinery. There are extensive uses of flow metering and monitoring systems in these areas of oil and gas fields. Typical divisions of the oil and gas system have been detailed in Fig. XII/4.1.0-1.

Different types of instruments in different oil and gas streams/areas have been listed in Table XII/4.1.0-2. As shown in Fig. XII/4.1.0-1, multiphase flows are used upstream before separation, and hence these are shown separately.

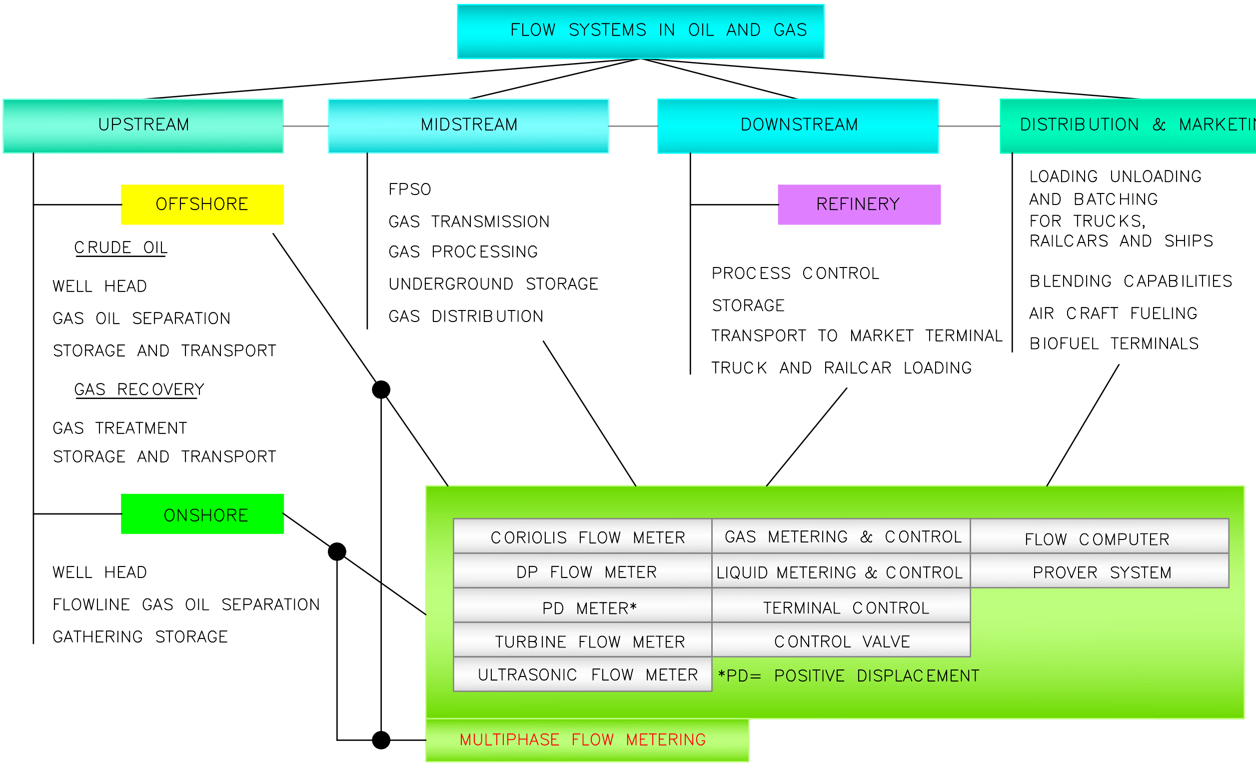

FIGURE XII/4.1.0-1 Flow meters in oil and gas.

TABLE XII/4.1.0-2 Flow Metering in Oil and Gas Stages (Major Usage)

Meters and Systems	Upstream Off/Onshore	Midstream Transportation	Petroleum Refining	Distribution and Marketing
Coriolis mass	X		X	
DP type	X			
PD meter	X	X	X	X
Turbine meter	X	X	X	X
USFM	X	X	X	X
Multiphase metering	X			
Flow computer and calculation	X	X		X

Continued

TABLE XII/4.1.0-2 Flow Metering in Oil and Gas Stages (Major Usage)—cont'd

Meters and Systems	Upstream Off/Onshore	Midstream Transportation	Petroleum Refining	Distribution and Marketing
Flow control system		X	X	X
Control valve			X	
Terminal control			X	X
Gas metering	X	X		
Liquid metering	X	X		X
Prover system	X	X	X	X

4.2.0 Instruments Used in Production Oil Separators

During the discussions in Chapter IX, it was noted that with the help of multiphase/two-phase instruments developed recently, people are trying to get rid of the separator. During discussions it has been noted that total separation and partial separation methods are used. Therefore, it is important to gather knowledge about separator instrumentation. There are two kinds of separator: a test separator—for periodic testing purposes and a regular production separator. Similarly, there are high-pressure and low-pressure separators. In this section short discussions are presented on separator instrumentation and other equipment and devices with separators. A typical production separator with pressure release valve and regulators is depicted in Fig. XII/4.2.0-1.

The separator can be for either two phase or three phase. In our discussions the three-phase separator, as shown in Fig. XII/4.2.0-1, has been considered. The main objective of separator is to separate the gas, oil, and water from the crude. With flow measurement it is possible to get much more additional information necessary for production and operation such as the following:

- Assessment of the condition and health of the well;
- Management of the well in declining stage;
- Quantification of production gas and oil;
- Fine tuning of the recovery operation to maximize retrieval of hydrocarbons [15].

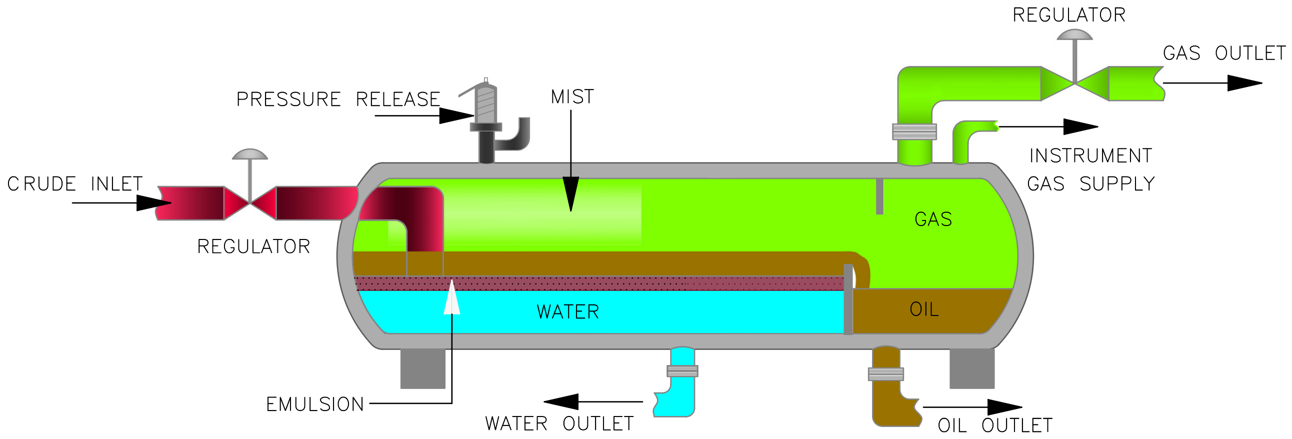

FIGURE XII/4.2.0-1 Production separator.

There are a number of instruments connected with the separator. These are listed below.

Pressure release: As per ASME code and API code 510 there should be means for pressure release. In view of this, separators are provided with a pressure relief valve to protect from overpressurized situations and alert you when gas volumes are vented.

Rupture disc: This is another way of protecting against overpressure situation. The disc breaks to relieve an overpressurized situation. Here the valve remains open until the disc is replaced.

Gas outflow: For proper functioning of the separator steady pressure needs to be maintained for gas outflow from the separator to the tank. If the pressure is too high, gas can become entrained in the oil where it will simply vent off from the tank, resulting in higher emissions and lost product [15]. In the case of low pressure, liquefied gas will be lost. Suitable regulators are installed in the gas line and gas is measured by a suitable gas meter as discussed in Table XII/4.1.0-1. The vortex meter is yet to receive approval for custody transfer.

Oil outflow: Like gas outflow, oil outflow is also measured. This flow is basically a quality check of the entire separator as well as that of the performance of the well. This delivery is an indication of the reservoir decline rates [15]. The oil outflow is critical because it is an allocation measurement to calculate any royalties owed to the land owner. The type of meters used for this purpose, with their pros and cons, are given in Table XII/4.1.0-1 and the water cut meter is discussed in Chapter IX.

Water outflow: Water production is a byproduct of the oil production process. Accounting of water also gives an indication of the well decline curve. Cumulative flow of water also alerts to emptying of the water tank. In some oilfields, how much water is produced must be reported for regulatory reasons [15]. Standard flow meters for oil and gas, along with electromagnetic flow meters, can be used for water.

Regulator: Regulators are used for pressure controls in crude inlets, as well as in the gas line to keep the pressure regulated. They are capable of handling high pressure. There are different kinds of regulators available for different sizes, styles, and types.

Instrument gas supply [15]: When using natural gas from the well to operate valves within the separator, you need to properly regulate pressure to the pneumatic controllers of the valves.

Sand detector: Though not directly a production parameter it is important to carry on regular operation. "Roxar sandlog" transmitter is an example of a sand detector and can be used for subsea applications also.

Flow-metering stations and associated uncertainty calculations are very important. They are guided by international standards of ISO, IEC, etc. It is not possible to discuss these at length within the limited scope of this book. In the next section detailed reference to the relevant standards has been listed along with major uncertainty formulas (only formulas, no derivations). Interested readers may refer to the relevant standards for details and calculation basis, etc.

4.3.0 Flow Metering Standards

In this section brief discussions and tables shall be provided for various standards and their significance in gas and oil flow, as well as major significant standards for various measurements (flow) related to petroleum oil and gas. In Table XII/4.3.0-1 only standards related to flow metering have been listed, for example, those for composition have not been taken into account here. [*The list has been prepared after going through available standards, as the standards are undergoing revisions, so the latest version as available should be consulted even though years are given here for the latest changes in the standards*].

In this connection, Norwegian Petroleum Directorate (NPD) directives and NORSOK standards I 104 and I 105 may be referenced also.

TABLE XII/4.3.0-1 Major Standards for Flow Measurements in Oil and Gas

Subject	Standard	Title
General	ISO/IEC guide 98-1	Uncertainty of measurement—Part 1: Introduction to the expression of uncertainty in measurement
General	ISO/IEC Guide 98-2	Uncertainty of measurement—Part 2: Concepts and basic principles
General	ISO/IEC guide 98-3	Uncertainty of measurement—Part 3: Guide to the expression of uncertainty in measurement
General	ISO/IEC Guide 98-4	Uncertainty of measurement—Part 4: Role of measurement uncertainty in conformity assessment
General	ISO/IEC Guide 98-5	Uncertainty of measurement—Part 5: Applications of the least squares method
General	NFOGM 2001	Handbook of uncertainty calculation, Ultrasonic Fiscal Gas Metering Station
General	NFOGM 2003	Handbook of uncertainty calculation, Fiscal Orifice Gas and Turbine Oil Metering Station
General	ISO 5168:2005	Measurement of fluid flow—Procedures for the evaluation of uncertainties
General	ISO 7066-2: 1988	Assessment of uncertainty in the calibration and use of flow measurement devices—Part 2: Non-linear calibration relationships
General	ISO 21748: 2010	Guidance for the use of repeatability, reproducibility and trueness estimates in measurement uncertainty estimation
General	API MPMS 13.1: 2011	Statistical concepts and procedures in measurement
General	API MPMS 13.2: 2011	Statistical methods of evaluating meter proving data
Liquid Applications		
Liquid flows	ISO 11631: 1998	Measurement of fluid flow—Methods of specifying flow meter performance
Liquid flows	API MPMS 5.1: 2008	General considerations for measurement by meters
Liquid flows	ISO 91-1: 1992 (2)	Petroleum measurement tables—Part 1: Tables based on reference temperatures of 15°C and 60°F
Liquid flows	ISO 91-2: 1991 (2)	Petroleum measurement tables—Part 2: Tables based on a reference temperature of 20°C
Liquid flows	ISO 2714: 1980	Liquid hydrocarbons—Volumetric measurement by displacement meter systems other than dispensing pumps

Continued

TABLE XII/4.3.0-1 Major Standards for Flow Measurements in Oil and Gas—cont'd

Subject	Standard	Title
Liquid flows	ISO 2715: 1981	Liquid hydrocarbons—Volumetric measurement by turbine meter systems
Liquid flows	ISO 4124: 1994	Liquid hydrocarbons—Dynamic measurement—Statistical control of volumetric metering systems
Liquid flows	ISO 9770: 1989	Crude petroleum and petroleum products—Compressibility factors for hydrocarbons in the range 638 kg/m^3 to 1074 kg/m^3
Liquid flows	ISO 10790: 1999	Measurement of fluid flow in closed conduits—Guidance to the selection, installation and use of Coriolis meters (mass flow, density and volume flow measurements)
Liquid flows	API MPMS 5.2: 2005	Measurement of liquid hydrocarbons by displacement meters
Liquid flows	API MPMS 5.3: 2009	Measurement of liquid hydrocarbons by turbine meters
Liquid flows	API MPMS 5.6: 2008	Measurement of liquid hydrocarbons by Coriolis meters
Liquid flows	API MPMS 5.8: 2005	Measurement of liquid hydrocarbons by ultra-sonic flow meters using transit time technology
Turbine meter	ISO 2715: 1981	Liquid hydrocarbons—Volumetric measurement by turbine meter systems
Turbine meter	ISO 6551: 1982	Petroleum liquids and gases—Fidelity and security of dynamic measurement—Cabled transmission of electric and/or electronic pulsed data
Turbine meter	API MPMS 5.3: 2009	Measurement of liquid hydrocarbons by turbine meters
Turbine meter	API MPMS 5.4: 2005	Accessory equipment for liquid meters
Turbine meter	API MPMS 5.5: 2010	Fidelity and Security of Flow Measurement Pulsed-Data Transmission Systems
PD meters	ISO 2714: 1980	Liquid hydrocarbons—Volumetric measurement by displacement meter systems other than dispensing pumps
PD meters	ISO 6551: 1982	Petroleum liquids and gases—Fidelity and security of dynamic measurement—Cabled transmission of electric and/or electronic pulsed data
PD meters	API MPMS 5.2: 2010	Measurement of liquid hydrocarbons by displacement meters
PD meters	API MPMS 5.4: 2005	Accessory equipment for liquid meters
PD meters	API MPMS 5.5: 2010	Fidelity and Security of Flow Measurement Pulsed-Data Transmission Systems

Continued

TABLE XII/4.3.0-1 Major Standards for Flow Measurements in Oil and Gas—cont'd

Subject	Standard	Title
Coriolis meter	ISO 10790: 1999	Measurement of fluid flow in closed conduits—Guidance to the selection, installation and use of Coriolis meters (mass flow, density and volume flow measurements)
Coriolis meter	ISO 6551: 1982	Petroleum liquids and gases—Fidelity and security of dynamic measurement—Cabled transmission of electric and/or electronic pulsed data
Coriolis meter	API MPMS 5.6: 2008	Measurement of liquid hydrocarbons by Coriolis meters
Coriolis meter	API MPMS 5.4: 2005	Accessory equipment for liquid meters
Coriolis meter	API MPMS 5.5: 2010	Fidelity and Security of Flow Measurement Pulsed-Data Transmission Systems
Ultrasonic flow meter (USFM)	ISO/DIS 12242	Measurement of fluid flow in closed conduits - Ultrasonic meters for liquid
USFM	ISO 6551: 1982	Petroleum liquids and gases—Fidelity and security of dynamic measurement—Cabled transmission of electric and/or electronic pulsed data
USFM	API MPMS 5.8: 2005	Measurement of liquid hydrocarbons by ultrasonic flow meters using transit time technology
USFM	API MPMS 5.4: 2005	Accessory equipment for liquid meters
USFM	API MPMS 5.5: 2010	Fidelity and Security of Flow Measurement Pulsed-Data Transmission Systems
Prover	ISO 7278-1: 1987	Liquid hydrocarbons—Dynamic measurement—Proving systems for volumetric meters—Part 1: General principles
Prover	ISO 7278-2: 1988	Liquid hydrocarbons—Dynamic measurement—Proving systems for volumetric meters—Part 2: Pipe provers
Prover	ISO 7278-3: 1998	Liquid hydrocarbons—Dynamic measurement—Proving systems for volumetric meters—Part 3: Pulse interpolation techniques
Prover	ISO 7278-4: 1999	Liquid hydrocarbons—Dynamic measurement—Proving systems for volumetric meters—Part 4: Guide for operators of pipe provers
Prover	API MPMS 4.1: 2009	Proving system—Introduction
Prover	API MPMS 4.2: 2003	Proving system—Displacement provers
Prover	API MPMS 4.4: 2010	Proving system—Tank provers
Prover	API MPMS 4.5: 2005	Proving system—Master Meter provers

Continued

TABLE XII/4.3.0-1 Major Standards for Flow Measurements in Oil and Gas—cont'd

Subject	Standard	Title
Prover	API MPMS 4.6: 2008	Proving system - Pulse interpolation
Prover	API MPMS 4.7: 2009	Proving system—Field Standard Test Measures
Prover	API MPMS 4.8: 2007	Proving system—Operation of Proving Systems
Flow Computer and Calculation (FCC)		
FCC	ISO 91-1: 1992 (2)	Petroleum measurement tables—Part 1: Tables based on reference temperatures of 15°C and 60°F
FCC	ISO 91-2: 1991 (2)	Petroleum measurement tables—Part 2: Tables based on a reference temperature of 20°C
FCC	ISO 4267-2: 1988	Petroleum and liquid petroleum products—Calculation of oil quantities—Part 2: Dynamic measurement
FCC	ISO 9770: 1989	Crude petroleum and petroleum products—Compressibility factors for hydrocarbons in the range 638 kg/m^3 to 1074 kg/m
FCC	ISO 91-1: 1992 (2)	Petroleum measurement tables—Part 1: Tables based on reference temperatures of 15°C and 60°F
FCC	ISO 91-2: 1991 (2)	Petroleum measurement tables—Part 2: Tables based on a reference temperature of 20°C
FCC	ISO 4267-2: 1988	Petroleum and liquid petroleum products—Calculation of oil quantities—Part 2: Dynamic measurement
FCC	ISO 9770: 1989	Crude petroleum and petroleum products—Compressibility factors for hydrocarbons in the range 638 kg/m^3 to 1074 kg/m
FCC	ISO 91-1: 1992 (2)	Petroleum measurement tables—Part 1: Tables based on reference temperatures of 15°C and 60°F
FCC	ISO 91-2: 1991 (2)	Petroleum measurement tables—Part 2: Tables based on a reference temperature of 20°C
FCC	ISO 4267-2: 1988	Petroleum and liquid petroleum products—Calculation of oil quantities—Part 2: Dynamic measurement
FCC	ISO 9770: 1989	Crude petroleum and petroleum products—Compressibility factors for hydrocarbons in the range 638 kg/m^3 to 1074 kg/m
FCC	API MPMS 21.2: 2004	Electronic liquid volume measurement using positive displacement and turbine meters

Continued

TABLE XII/4.3.0-1 Major Standards for Flow Measurements in Oil and Gas—cont'd

Subject	Standard	Title
Gas Flow		
General	R140:2007	Measuring systems for gaseous fuel
General	R137—1:2006	Gas meters—Part 1: Requirements
DP type	ISO 5167-1: 2003	Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full—Part 1: General principles and requirements
DP type	ISO 5167-2: 2003	Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full—Part 2: Orifice plates
DP type	ISO 5167-3: 2003	Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full—Part 3: Nozzles and Venturi nozzles
DP type	ISO/TR 12767: 2007	Measurement of fluid flow by means of pressure differential devices—Guidelines on the effect of departure from the specifications and operating conditions given in ISO 5167
DP type	ISO/TR 15377: 2007	Measurement of fluid flow by means of pressure-differential devices—Guidelines for the specification of orifice plates, nozzles and Venturi tubes beyond the scope of ISO 5167
DP type	ISO 9300: 2005	Measurement of gas flow by means of critical flow Venturi, nozzles
DP type	AGA Report Nr 3-1: 2009 API MPMS 14.3.1	Orifice metering of natural gas Part 1: General equations & uncertainty guidelines
DP type	AGA Report Nr 3-2: 2006 API MPMS 14.3.2	Orifice metering of natural gas Part 2: Specification and installation requirements
DP type	AGA Report Nr 3-3: 2009 API MPMS 14.3.3	Orifice metering of natural gas Part 3: Natural gas applications
DP type	AGA Report Nr 3—4: 2006 API MPMS 14.3.4	Orifice metering of natural gas Part 4: Background, Development implementation procedure
USFM	ISO 17089-1 and -2: 2010	Measurement of fluid flow in closed conduits—Ultrasonic meters for gas—Part 1: Meters for custody transfer and allocation measurement; Part 2: Meter for industrial applications
USFM	AGA Report Nr 9: 2007	Measurement of gas by multipath ultrasonic meters
USFM	AGA Report Nr 10: 2003	Speed of sound in natural gas and other related hydrocarbon gases

Continued

TABLE XII/4.3.0-1 Major Standards for Flow Measurements in Oil and Gas—cont'd

Subject	Standard	Title
Coriolis	ISO 10790:1999 Amendment 2003	Measurement of fluid flow in closed conduits—Guidance to the selection, installation and use of Coriolis meters (mass flow, density and volume flow measurements):Guidelines for gas measurement
Coriolis	AGA Report Nr 11: 2003	Measurement of natural gas by Coriolis meter
Turbine	ISO 9951:1993	Measurement of gas flow in closed conduits—Turbine meters
Turbine	AGA Report Nr 7: 2006	Measurement of natural gas by turbine meter
Multiphase flow	NFOGM: Handbook Revision 2: 2005	Handbook of multiphase flow metering
Multiphase flow	API MPMS RP 86: 2005	Recommended practice for measurement of multiphase flow
Multiphase flow	API MPMS Publ 2566: 2004	State of the art multiphase flow metering
Multiphase flow	ISO/PRF TR 11583: 2011 (1)	Measurement of wet gas flow by means of pressure differential devices inserted in circular cross-section conduits

4.4.0 Metering Stations

As seen from Section 4.1.0 above, it is clear that there are pipeline metering stations in oil and gas areas at different stages. In this section, gas and liquid measuring stations are discussed. Leakage detection is an important issue in pipeline metering and has been included.

4.4.1 GAS METERING SYSTEM (STATION)

Pipeline gas metering stations are meant to continuously monitor the quality and quantity of natural gas in a pipeline to cover the following:

- Calorific value or latent energy for combustion (pricing);
- Concentration of sulfur;
- Hydrocarbon and water dew point;
- Natural gas volume and mass flow measurement and calculations.

Of these, flow measurement is of major concern in this book. Major instrumentation systems and devices include but are not limited to multipath ultrasonic flow meters, process gas chromatographs, and computer workstation flow control valves, automatic shutdown valves, and control systems. The main equipment includes filters, heaters, pressure reducers and regulators, and flow-metering skids. In addition to these, each station is generally equipped with drains for collection and disposal, instrument gas system, and storage tanks [16]. Some of the major process and mechanical systems include the following:

1. Filter separators;
2. Meter skid piping;
3. Heaters;
4. Pressure reduction and regulation;
5. Sound pressure;
6. Overpressure protection;

7. Cathodic protection;
8. Building.

Apart from these the flow metering and control system include but are not limited to:

9. Metering system: Places where custody transfer takes place are the most important, so with reference to that, the flow rates of gas need to be measured at a number of locations for the purpose of monitoring the performance of the pipeline system. There will normally be two runs of pipe with a calibrated metering orifice in each run for the custody transfer metering station. When used a multipath ultrasonic meter should meet the requirements of AGA 9 and other standards mentioned earlier (including the standards for uncertainty determination). As necessary, the meter tubes will be equipped with a flow conditioner. The fully assembled meter tubes should be calibrated at line pressure and full-flow conditions prior to use. Normally, the ultrasonic meter tubes will be designed for a minimum 10D upstream length from the flow conditioner to the meter and 5D lengths downstream of the meter [16]. Suitable measures should be taken into account to eliminate pulsation and errors.
10. Flow control valve and flow controller: A control valve is installed downstream of the meter run to control flow through and the delivery pressure. This valve will primarily operate to limit the station throughput to prevent exceeding the meter capacity. The flow control valve is regulated by flow computer and calculating (FCC) methods discussed in the standards listed in Table XII/4.3.0-1. The control valves are normally open type to minimize pressure losses through the station. The flow computer is meant to monitor and control the facilities as well as perform custody transfer quality measurement, including communication with the DCS and system control and data acquisition (SCADA) system. Gas chromatograph (GC) is meant to determine the gas composition for purposes of calculating the gas gross heating value and a moisture analyzer is used to measure the water content of the gas system. GC and moisture instruments exchange data with the flow computer and calculation (FCC) unit for calculating the total gas heating value in the metered gas. A gas sample is taken from a continuously flowing location on the meter and regulator skid. The gas sample is secured at low pressure to minimize the lag time utilizing a self-regulating sample probe and routed to the gas chromatograph and moisture analyzer [16].
11. Automatic shutdown: An automatic shutdown system with a remotely operated shutdown valve is installed at the pipeline connection. This valve is equipped with pneumatic controls, a hydraulic manual override, and open/close limit switches. Blow down of the meter station piping is accomplished by a vent stack located on the station inlet piping and vents on the meter skid located downstream of the meter and downstream of the flow control valve [16].

4.4.2 LIQUID MEASURING SYSTEM (STATION)

The liquid measuring system is part and parcel of the petroleum or hydrocarbon liquid distribution system. It uses advanced metering technologies, control system, and flow computing and calculation system. Liquid metering can be from a single line to several lines handling different kinds of liquids with dedicated provers for individual lines. The application areas of liquid measurement stations for metering of crude oil, refined products, NGL, LNG, and chemicals include but are not limited to the following:

- Pump stations feeding pipelines;
- Terminal stations feeding several users;
- Metering at inlet locations on the pipeline;
- Products segregated for transportation to separate the liquids [17].

Depending on the application and metering requirements there can be several parallel lines

being fed from a single header. Again, based on the application, meters can be grouped and may be fed through manifolds with a suitable interlock. The arrangement mainly depends on the application. Major equipment includes but is not limited to the following:

1. **Mechanical piping arrangement** (application specific);
2. **Inlet block valve** (facilitates maintenance);
3. **Strainer**;
4. **Downstream block valve** (for allowing/disallowing flow through the meter);
5. **Miscellaneous instrumentation:** Pressure and temperature instruments for volume, density corrections, etc. These are connected to the flow computer for flow computations and metering calculations. There will also be status signals;
6. **Flow computer:** These are meant for flow computation and metering calculations. They also support the operator interface for monitoring and control. The system is complete with an operator interface including HMI;
7. **Prover:** There are various designs discussed later in this book;
8. **Four-way switch:** For flow diversion in prover;
9. **Digital counter and switch:** Start/stop digital counter;
10. **Flow meters:** Basic requirements for meter selection include:
    - High accuracy (∼0.25% AR)
    - High turndown: 10:1
    - Wide flow range coverage
    - Comparatively lower permanent pressure loss;

    Therefore, flow meter types used mainly include:
    - Turbine meter
    - Ultrasonic flow meter
    - Positive displacement
    - Coriolis mass flow meter;

    Of these the first two, on account of their higher flow capacities, lesser foot print and weight (and also not much permanent pressure loss), are the preferred ones. However, both types require long straight length sections, so for practical use flow conditioners are used.
11. **Flow control valves:** These are used for equalization flow in all meters, i.e., to remove imbalance should it exist, flow meters may be run at nearly their maximum range to increase throughput. However, normal metering flow should match with the normal operating range. Flow control valves should be designed to close against the maximum upstream pressure that will occur, with no pressure downstream, in order to avoid damage when the valve operates against full differential pressure [17].

For long pipe line leak detection it is a crucial safeguard device, which is elaborated on in the next section.

4.5.0 Leak Detection in Long Pipe Line

When petroleum products are transported over a very long distance it is critical and crucial to detect any leak in the pipeline. This is important for environmental and personal safety. However, even a small leak could turn out to be a catastrophe. There are three distinct types of leak detection systems possible: visual, external instrument, and instrumented internal pipeline type. A leak detection system (LDS) with nonintrusive ultrasonic flow meters is the most popular and is used mostly in pipeline applications. The detection method and locating of the leak are important considerations.

4.5.1 ADVANTAGES OF USFM FOR LEAK DETECTION

On account of some distinct advantages, USFM is used most often as the leak detection system (LDS).

Major advantages of using nonintrusive USFM include the following advantages:

1. No moving parts;
2. Nonintrusive, no pipe penetration is necessary;

3. Inherently bidirectional;
4. No additional instrument valve necessary to remove for maintenance during operation;
5. In addition to measuring fluid velocity, USFM can measure at the speed of sound and its changes hence can detect the fluid type in the pipeline, i.e., density, viscosity, etc.;
6. Ability to detect fluid identification and liquid properties;
7. Ability to detect from small to large product release in real time, i.e., high turndown ratio;
8. Extremely sensitive to *no*-flow condition.

With these details in mind let us look into the details of the system.

4.5.2 DESCRIPTIVE DETAILS OF THE LEAK DETECTION SYSTEM

Core elements of the leak detection system based on the compensated mass balance principle are dual pair clamp on US transducers mounted at the beginning and end of the measured section [18]. There can be such measurement stations, e.g., every 100–150 km. The actual distance is influenced by the environmental protection need as well as geographical topology. In order to take care of fluid temperature variation a suitable temperature element (RTD) is used downstream of the US sensors. Similarly, the ambient temperature variation is taken care of by another set of RTDs at the local station.

1. **Leak detection:** As stated earlier, in addition to measuring fluid velocity, USFM also measures the sonic velocity of the liquid in the pipeline. As the sonic velocity is a signature characteristic of the fluid, the master station through suitable software is able to recognize the fluid. Also, USFM measures functions as both a flow meter and density meter [19]. It is known that sonic velocity is affected by the density of the medium, so USFM infers the liquid density by measuring the sonic velocity and establishing the relationship between density and the measured sonic velocity. Therefore, a nonintrusive mass flow measurement system is based on the actual measurement of the pipeline mass input, versus the actual measured pipeline mass output. Therefore, the meter employs the mass balance of a compressible liquid (compensated volume balance is also available, e.g., from Siemens).
2. **Process conditions:** Temperature is measured and compensated, whereas pressure is seen through sonic velocity as it has a direct impact on density. By measuring the sonic velocity, with the help of change pressure, condition is calculated.
3. **Local and master station configuration:** Local information/data collection by the transducers and RTDs are sent to the local station processor for local sampling and processing. In addition to the local computing station, there will be one master station as shown in Fig. XII/4.5.0-1.

   This is also an intelligent flow control and computing unit. The major functioning is to run a software for leak detection. Each local station is connected to the master station through a switch circuit (basically a way of software polling of the local station by the master station). The master station collects the temperature, liquid density, liquid viscosity, etc. to recognize the liquid and associated changes therein so that along with this information and flow it can detect the leak by mass balancing (volume balancing [18]). Additionally, important diagnostic information, such as the transducer signal strength and aeration, is also sent to the master station to help in determining the health of the meter and the quality of the liquid. All these information are measured by each site station at least 10 times per second [19].
4. **Leak location:** Location of a leak in a long pipeline is extremely important. There can be several products, each of which has a different speed of sound that a pressure transient will travel through between two measuring points. When the products between two site stations are known, the master station can calculate the arrival time. In LDS, leak location is determined by measuring the amount of time the

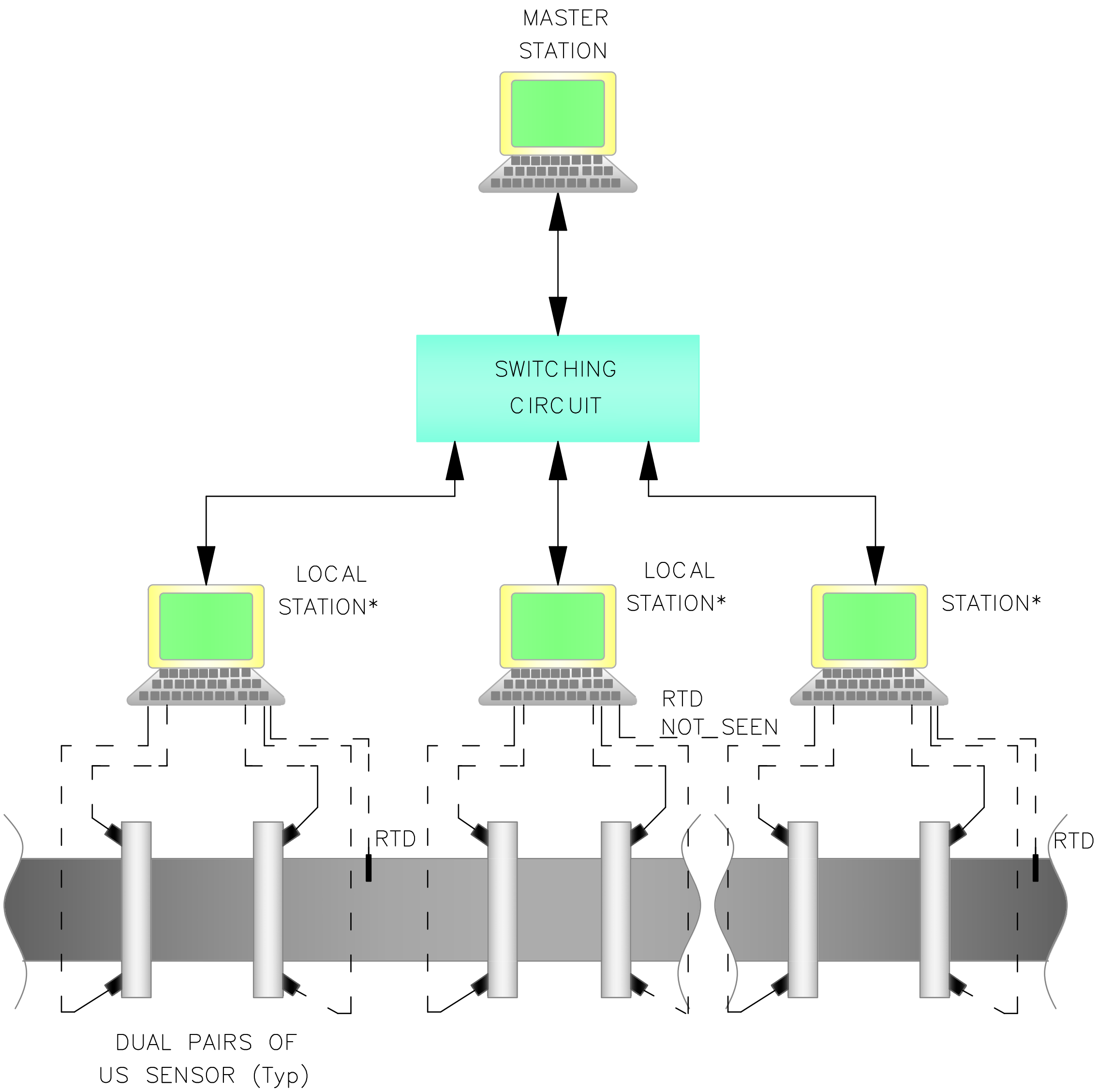

FIGURE XII/4.5.0-1 Leak detection system. *Each local station with ambient temperature compensation.

Digmesa Technology: Digmesa technology meets the stringent hygienic requirements of the manufacturing process to simple dispensing measurement. This is a cost-effective solution for measurements; be it beverage dispensing or coffee machine or controlling fluid in hospital disinfecting activities. The flow sensor monitors the whole process to ensure that a liquid has been dispensed even under the most difficult condition. This Swiss technology of flow sensing utilizes Laser or Ultrasonic technology. It can sense very low flow as low as 0.08 L/min.

FIGURE XII/6.3.0-1 DIGMESA technology.

low-pressure (due to leak) wave takes to travel from its source to each of the segment's local stations. The site stations can sense the low-pressure wave's arrival by its effect on the density of the fluid, which is measured many times each second [19]. The speed of pressure transient in the pipeline is determined by the speed of sound for the product being transported. The measurements are done by sampling the data many times and integrating the

same over a fixed time period and comparing this with a leak threshold over that time period.

5. **Zero flow:** Zero flow conditions are frequently found in pipeline transportation. There can be many lines in zero flow for a long period. Also, zero flow occurs during bidirectional flow requirements. USFM responds nicely to this condition.

There are several other leak detection systems, but the USFM type provides better performance.

Various flow meters discussed in the above sections are used in refinery and petrochemical plants. In the following sections these processes are discussed.

4.6.0 Petroleum Refinery Application

The basic refining process includes but is not limited to the following major headings:

- Treatment;
- Conversion;
- Separation;
- Blending;
- Alkylation;
- Catalytic reformation;
- Hydro-cracking;
- Coking;
- Isomerization;
- Polymerization;
- Etherification.

Major conversions of crude oils and other input streams in the refinery include the following refined products:

- Liquefied petroleum gases (LPG);
- Gasoline;
- Jet fuel;
- Kerosene (for lighting and heating);
- Diesel fuel;
- Petrochemical feedstocks;
- Lubricating oils and waxes;
- Home heating oil;
- Fuel oil (for power generation, marine fuel, industrial and district heating);
- Asphalt (for paving and roofing uses).

Flow metering covers a wide variety of flow meters that are deployed in such applications which include but are not limited to: DP type meters, PD meters, electromagnetic, turbine, vortex meters, and mass flow meters of both types.

4.7.0 Petrochemical Application

Hydrocarbon processing plants, such as petrochemical and chemical plants, always aim to optimize the production of products used in a wide variety of end usages, which include but are not limited to cosmetics, synthetic rubber, plastics, automotive lubricants, pharmaceuticals use, cleaning products, etc. It is needless to mention the importance of flow meters for such an optimization process. Such flow metering in petrochemical plants can range from upstream production to feedstock, including intermediate stage and processing, such as gas flow measurement, catalyst injection, batching and blending, custody transfer, and fugitive emissions monitoring. Many critical decisions can be taken faster by capturing, managing, and analyzing the right flow measurement data at the right time. Flow metering covers a wide variety of flow meters that are deployed in such applications including but limited to: DP type meters, PD meters, electromagnetic, turbine, vortex meters and mass flow meters of both types. Major application areas include the following:

- Chemical batching;
- Dosing/blending;
- Steam flow;
- Lubricating oil;
- Process cooling;
- Pressure regulation;
- Leak detection;
- Waste treatment;
- Emissions monitoring;
- Fiscal measurement.

Apart from custody transfer and fiscal measurement, and for accounting purposes, accurate, real-time flow data are essential to reduce

resource consumption and make the best use of expensive raw materials. Also, for environmental protection and monitoring of greenhouse gas emissions, it is also important for flow metering applications.

With this the discussions on oil and gas come to an end and we now investigate flow measurements in pulp, paper, and chemical plants.

5.0.0 PULP, PAPER, AND CHEMICAL INDUSTRIES

Pulp and paper industries involve many chemicals and corrosive materials. In this section discussions cover pulp paper and chemical industries under one heading that covers the requirements of flow instruments which need to work with very corrosive, abrasive materials simultaneously at high temperature. In all these cases, material selection is very important for the flow meters. In this section efforts are made to cover material selection at length. Chemical plants can be of widely varied types—hence the process description cannot be included. Therefore, the discussions start with an outline of the basic process of pulp and paper plants which involves the following majors steps:

1. **Pulping:** This process involves mechanical and chemical processing of wood chips. Mostly used chemical pulping involves high temperatures, corrosive and abrasive substances, and vibrations, hence highly reliable measurement and controls are necessary.
2. **Bleaching:** Depending on its density, chemical pulp is transported via pumps, flow distributors, or conveying spirals to the bleaching tower. The process is also carried out at high temperature and chemical addition.
3. **Inventory preparation:** Holding large quantities of prepared stock in storage towers and chests for continuous operation in a pulp and paper plant.
4. **Paper machine:** This is the heart of the paper plant. Paper sheet formation is done here. At the head box, pressure and speed are kept constant to ensure a uniform paper sheet is formed. During the drying process, a condensate film forms on the inside wall of the drying cylinder, affecting the heat efficiency of the transfer to the paper.
5. **Wet end:** After bleaching, pulps from different sources are mixed as needed for various products and mechanically refined prior to delivery to the head box. Sizing agents, dyes, and additives are added precisely to produce the desired paper characteristics.
6. **Waste treatment:** Wastes which come together from different processes are suitably monitored and treated prior to disposal. The process of treatments required is very much dependent on environmental regulations at the place.
7. **Utilities:** There are various steam, boiler, and recovery utilities in a pulp and paper mill that need to be controlled. One of the most important is the recovery of spent cooking chemicals.

5.1.0 Major Challenges and Aims of Flow Measurement

As indicated above major flow measurement issues arise out of the chemicals used in these plants. These materials at times pose serious problems towards material selection for the different kinds of flow meters to be used in these plants.

1. **Major challenges:** Flow measurements in pulp paper mills and chemical plants face major challenges due to various kinds of chemicals, which in some cases are very corrosive and aggressive. Major challenges in pulp paper and chemical plants include but are not limited to the following:
   - Extremely aggressive chemicals;
   - High-viscosity fluid flow;
   - Corrosive materials;
   - Abrasive materials;
   - High pressures and/or temperatures.

   Naturally, the right selection of flow meter technology in the most suitable

configuration is extremely critical for efficient working of the flow meter in that environment and conditions.

2. **Aim of flow meter selections:** The following are the aims of flow meters in general but more so in these plants where there will be a chance of instrument failure due to corrosion/abrasion:
   - Reliable and stable operation under given conditions;
   - Ability to withstand the harsh conditions meters need to face;
   - Good accuracy of measurement;
   - Good repeatability;
   - Easy to install and easy calibration;
   - Less downtime and lower maintenance;
   - Low-cost ownership.

The discussion starts with various kinds of flow meters normally encountered in pulp and paper plants. While on the subject other chemical plants shall be covered also.

5.2.0 Flow Meters in Paper and Chemical Plants

There are many types of flow meters used in pulp and paper plants. Meter types and typical application areas have been listed in Table XII/5.2.0-1.

5.2.1 USE OF DP TYPE METERS

DP type meters have been in use in different plants over many decades for their reliable operation and as cost-effective solutions to measure volumetric flow, especially in applications with large line sizes—typically 8 inch diameter. When DP type meters are used in conjunction with measurement of pressure and temperature (as required) it can give mass flow also. With suitable selection of materials it can be used in many corrosive applications. DP flow measurement can be used with conductive and nonconductive fluids, allowing it to be used with a wide range of gases and liquids. Therefore, in the case of chemical plants they find direct use in utilities, such as water, steam, and in some fuel flow applications also. On account of the primary element, there will be permanent pressure losses but with suitable selection of primary element this permanent loss can be minimized. For chemical plants with heavy dust problems, Annubar/Krell's orifices (Chapter II) can be adapted when permitted by the process. There are several challenges to DP type measurement. One is wet leg issues. "Wet leg" is the term used to describe the impulse line connection between the DP transmitter and the primary flow-sensing element [20]. Measuring gas at times can be trapped in the wet leg. Clogging of the wet leg issue has

TABLE XII/5.2.0-1 Instrument Type and Applications in Pulp & Paper Plant

Meter Type	Application Areas
Electromagnetic	Stock, liquor, chemicals, coating kitchen, coating, lime mud and water in digester blow lines, additives, etc.
Coriolis	Density, volume concentration, high-value chemicals, coatings, fuel (gas/oil) and steam: stuff box—chemical feed, coating kitchen, and coating
DP type	Utilities such as steam, fuel
Vortex	Saturated and superheated steam (with pressure/temperature compensations)
USFM	Low-conductive clean liquids
SONAR	Digester blow line

been dealt with in detail in Section 1.1.0 in this chapter and may be referenced. As in paper and chemical plants use corrosive fluids so, DP transmitters for flow measurements are often used with suitable seals such as remote seals are often used based on applications. So, while selecting DP/multivariable transmitters same should be borne in mind.

5.2.2 USE OF MAGNETIC FLOW METERS

Electromagnetic flow meters are used extensively in these plants at various applications, as shown in Table XII/5.2.0-1. The only limiting criterion is low conductivity, otherwise it can be used for most fluid applications.

1. **Reasons for choice:** On account of the following reasons the electromagnetic flow meter is the preferred flow meter in these plant applications:
   - *Accuracy:* Good accuracy;
   - *Noise:* Good noise (of slurries) mitigation properties;
   - *Materials:* Available with a wide range of materials to match process needs for lining and an electrode for high-temperature and liquid permeation applications;
   - *Obstruction:* Obstructionless (fiber does not build up in meter);
   - *Plugging:* No chances of plugging as no ports or impulse lines involved;
   - *Pressure drop:* Full diameter with practically no pressure drop across meter;
   - *Communication:* Fieldbus communication possible;
   - *Maintenance:* Lower maintenance requirements;
   - *Cost:* Cost-effective (for size requirement).
2. **Major problems and issues:** There are a good numbers of issues associated with fluids in chemical plants and pulp and paper plants. A few specific issues are listed below as examples:
   - *Slurry noise:* High slurry noise;
   - *Corrosion:* Highly corrosive chemicals;
   - *Consistency:* Stock consistency variations;
   - *Viscosity:* Viscosity variation;
   - *Permeation:* Liquid permeations are seen in the form of blisters and bubbles that can cause premature failure of the liner;
   - *Fiber:* Fiber length;
   - *Abrasive materials:* Highly abrasive fluids (with solids);
   - *Adhesives:* Adhesive chemicals and adhesion of wood resin, dye.
3. **Possible solutions:** For stable and accurate measurement with longer life-time solutions the listed below may be applied. These are general solutions, the reader can contact the manufacturer for further details.
   - *Dual frequency:* Dual-frequency excitation (with selection options: refer to Subsection 4.4.2.2 of Chapter V). High slurry at low frequency may pose problem. Therefore, based on the application suitable high-frequency selection options are available [21];
   - *Lining:* A wide range of lining selections is possible. These include ceramics, PFA (with metallic earthing) lining, as necessary for adhesive fluid applications;
   - *Electrode coating:* Protective electrode coatings are available;
   - *Sensing:* For adhesive fluids, as necessary, external capacitance sensing is available;
   - *Diagnostics:* Advanced diagnostics are available for the meter. It is possible to detect lower signal to noise (S/N) ratio in advance, to take corrective action for easy changing of the coil drive to the frequency that provides the strongest signal [22];
   - *Permeation improvement:* The temperature gradient may increase permeation rates. This is common in paper machines, as increased temperature gives better production. The choice of the correct Teflon PTFE lining and their manufacturing process mostly mitigate the problem. In this connection Fig. XII/5.2.2-1 may be referenced for permeation and liner manufacturing issue. Liners like Sintered PTFE Teflon Liner (thicker) Sleeves and Virgin Transfer Molded PFA can be a good choice [22]. Use of insulation can be used to reduce the temperature variation between the process and the ambient temperature.

Permeation: *Permeation (imbuing) is the penetration of a* ***permeate*** *(liquid, gas, or vapor) through a solid. Basically permeation is the molecular diffusion of a fluid or vapor through a material. It is characterized by bubbles forming underneath the liner sleeve. Permeation depends on: Concentration gradient of the permeate, material's permeability and materials' mass diffusivity i.e. process fluid chemistry, temperature, pressure, quality of the liner, and liner thickness. In EMFM permeation can occasionally affect PTFE Teflon lined flow tubes in high temperature applications. PTFE in compression molding with special manufacturing technique can reduce permeability rate in EMFM .*

FIGURE XII/5.2.2-1 Permeation.

5.2.3 USE OF ULTRASONIC FLOW METERS

Clamp-on ultrasonic transducers inherently enjoy the advantage of installation and mounting flexibility and can be retrofitted very easily as they are simply mounted on the outside of the pipe. On account of its nonintrusive noninvasive nature, it has practical advantages of no wear and tear by the flowing medium due to abrasion/corrosion, no risk of liquid leakage or fugitive gas emissions, no pressure loss and, above all, unlimited plant availability. Another advantage of USFM, as already discussed in Chapter V and in connection with leakage detection here, is that by measuring sonic velocity, it can take care of process condition changes. Therefore, product characteristics like concentration and density can be monitored continuously online. As a result of this it is possible to determine the flow rate and mass flow rate of liquids as well as gases with the help of transit time USFMs which can measure flow in both directions. A wide range of ultrasonic transducers, mounting fixtures, and transmitters guarantee ideal adaptation to the individual measurement task, independent of pipe material, wall thickness, and measurement range—even within hazardous areas (FM Class I, Div. 1 and 2, ATEX) [23]. These meters are available for a wide range of process and ambient temperatures and independent of pipe diameter. USFMs also offer diagnostic features. In view of all these characteristics, USFM can be an easy choice as flow meters in chemical plants, integrated chemical plants with highly complex networks of mass and energy flows [23], along with problems of corrosion abrasions. Added to this they have no pressure loss. However, they have limitations in fluid medium with fibers. These are available for use in hazardous area applications also, with necessary approvals/certifications from appropriate authorities (e.g., ATEX) for safe operations. In this connection, the discussions in Sections 1.2.1 and 1.2.2 in this chapter may be referenced.

5.2.4 USE OF VORTEX

Sizing of the vortex is extremely important. A properly sized vortex is very good in measurement fluids, including steam (saturated and superheated). Bluff body design is part of the manufacture design, and so sizing must be done with manufacturers. Typical vortex designs have small free spaces or crevices around sensors or shedder bars to create the movement needed to create vortices. Coating or particulate matter in the fluid can clog the crevices and inhibit sensor movement, resulting in inaccurate flow measurement [20]. Minimum flow rate ("low flow cutoff") is necessary for the vortex to operate, so often concentric reducers are recommended.

In this connection, Section 1.2.3 of this chapter may be referenced for further details.

5.2.5 MASS FLOW METERS

In chemical plants, especially in batch processes, mass balance is usually used in recipes. Therefore, the use of direct mass flow measurement is always the first preference. Direct mass flow measurement over wide turndowns with varying fluid properties is used in chemical plants. On account of the ability to measure density and concentration measurements with high-accuracy and repeatability make them suitable for chemical batch processes. Added to these, mass flow meters do not require any straight length, so mounting and installations are easier. Direct mass measurement eliminates the cost and maintenance of temperature and pressure transmitters, and flow computers. However, cost, pressure drop, and nonavailability for large diameters make their use limited at times. However, thermal mass flow meters at times are used in certain cases in place of Coriolis flow meters for mass flow measurements. The use of insertion type thermal mass flow in some chemical plants is quite popular, especially for cases when the sensor is well protected and does not come into contact with the flowing medium. The use of a thermal mass flow meter (both direct and bypass designs) in compressed air systems, raw materials, and finished products in chemical plants is quite common.

5.2.6 SONAR FLOW METERS IN PULP AND PAPER PLANTS

As indicated in Table XII/5.2.0-1, there are a number of other type flow meters used. Sonar, described in Section 9.0.0 of Chapter V, can be applied.

(Courtesy: CiDRA Chemical Management, Inc.)

1. **Air flow in head box:** One such is a noninvasive way to measure and regulate air flow in a head box. The quality of the papermaking process is improved with suitable control of air flow at the head box. This provides a number of benefits such as the following:
   - Reduction in paper breakages;
   - Higher run-ability;
   - Less pinholes and dirt spots;
   - Reduction in defoamer (10%−40% saving) and retention of chemical consumption [24];
   - Improved formation;
   - Stabilized paper caliper;
   - Good retention controls;
   - Better water removal;
   - Improved and stabilized operation of vacuum and pumping.

   Air and CO_2 in the head box stock cause deterioration of paper quality on account of the following:
   - Pinhole formation;
   - Dirt spots;
   - Affecting water removal;
   - More breaks;
   - Increased bacterial activity;
   - Requirement for deaeration chemicals.

   Noninvasive sonar technology measures in real time the amount of entrained air in the head box. This helps to enable optimizing chemical dosing. It can be used to measure total air content (both entrained and dissolved gas) in the head box stock. It also enables automated head box stock air content control to reduce the consumption of deaeration chemicals [24].
2. **Digester blow down line:** Electromagnetic flow meters are mostly used in this application. However, there can be measurement error or inaccuracy on account of wear, deposits, conductivity variations, and debris. Sonar type flow meters are noninvasive and are not affected on account of these issues. Therefore sonar can be used in this particular application. Also, like electromagnetic flow meters, sonar measurements can also be full bore type with no permanent pressure loss. They are also unaffected by any abrasion effects. They are better suited for process control in some cases.

After going through the instrument application in pulp, paper, and chemical plants, we now investigate instrumentation in the food and pharmaceutical industries.

6.0.0 PHARMACEUTICAL, FOOD, AND BEVERAGE INDUSTRIES

During the discussions in Chapter XI, Section 6.1.2, on batch process operation, it was shown that food, beverage, and pharmaceutical industries operate in a batch process mode and each of them demands a special kind of measurement—be it in yeast growth or juice preparation—to name a few. Also, in these industries, the major thrust is on hygienic use and material selection for various meters. Each of these industries has separate requirements and demands flow meters need to meet. For example, a tablet manufacturing unit may use a loss-in-weight feeder for dosing and mixing of recipe. On the other hand, beverage industry use of turbine meters is very common. So, prior to going into further details, we now look at the various types of meters used in these industries. It must be noted that in pharmaceutical, food, and beverage industries there are huge numbers of industries with wide variations and specialties of instruments that might be used. It is practically impossible to cover them all. Here commonly used flow meter types have been covered. The discussions start with types of instruments used in pharmaceuticals, food, and beverage industries.

6.1.0 Instrument Types Used in Pharmaceutical, Food, and Beverage Industries

Listed in Table XII/6.1.0-1 are the flow instruments normally encountered in pharmaceutical, food, and beverage plants.

TABLE XII/6.1.0-1 Instrument Types in Pharmaceutical Food and Beverage (F&B)

Instrument	Plant Type	Typical Features
Turbine	Pharmaceutical	Axial type or Pelton wheel magnetic pickup; bearing: ceramic/sapphire. Accuracy/repeatability: 1%/0.25% AR wide ranges; TD300:1; over range: 150%. Air and liquid flow measurement for pill coating. Ultra pure water flow
Turbine	Food beverage	Axial type; magnetic pickup; bearing: ceramic/sapphire. Accuracy/repeatability: 0.5%/0.25% AR; wide ranges; TD200:1; over range
Thermal mass FM	Pharmaceutical	Capillary/immersion type; wide flow range: accuracy/ repeatability: 1–2% AR/0.25% AR. For gas flow measurements
Coriolis mass FM	Pharmaceutical	Both bent and straight tube Coriolis are popular. Water for injection, reverse osmosis and deionized water measurement. High rangeability
Electromagnetic	Pharmaceutical and food beverage	Both AC/DC type, hygienic grade with accuracy 0.25%–0.5% AR velocity of measurement between 0.3 and 10 m/s. Also used in waste water lines
USFM	Pharmaceutical and food beverage	Both transit time and Doppler type used. Preferred selected from hygienic point of view. Available in various pipe sizes. Accuracy 0.1% AR. Additional inherent advantages like clamp on design, diagnostics already discussed

Continued

TABLE XII/6.1.0-1 Instrument Types in Pharmaceutical Food and Beverage (F&B)—cont'd

Instrument	Plant Type	Typical Features
PD Meters	Food beverage	Reciprocating piston type and other PD meters are used to add ingredients, chemicals, and additives in the manufacturing process. Normally these are provided with a local counter/totalizer
Digmesa*	Food beverage	Special flow sensors used for precision measurement of flow. Laser/US technology-based Digmesa type sensor technology is found in almost all dispensing machines in beverage industries *Refer to Fig. XII/6.3.0-1
Loss in weight feeder	Pharmaceutical	Dosing and mixing of recipes. Additive additions. Mostly used for tablet making. Accuracy: 0.5% AR

(For solid flow meters in food industries for granular items Chapter VIII may be referenced.)

6.2.0 Discussions on Flow Meters in Pharmaceutical Industries

In this section short discussions on major instruments used in pharmaceutical industries have been covered.

6.2.1 ULTRASONIC FLOW METER APPLICATIONS

In pharmaceutical industries USFMs are found both as permanent as well as battery-operated portable types, which can be run for around 12 h.

1. **General features:** Hygiene and cleanliness are always a top priority in the pharmaceutical industry. Naturally, clamp-on ultrasonic flow metering technology could be an ideal solution as it does not come into contact with the measuring fluid, eliminating the chances of contamination. In pharmaceutical industries there are some temporary needs for which there is practically no alternative to clamp-on ultrasonic technology. USFM in monitoring flow in feed water flow measurements is very common. Both transit time types as well as Doppler types have been found in this industry, as in certain applications there will be solid in liquid. These are available in various sizes from as small as 25 mm to very large-sized pipe. As already discussed, the self-diagnostic features of USFM keep their choices ahead of other types. These instruments support various forms of communication, e.g., HART, Fieldbus, etc.
2. **Portable type specialties:** Portable USFMs are common in this industry to monitor velocity in certain flow lines, especially in ultrapure water lines. Portable clamp-on flow meters are of choice for servicing and maintenance activities and a few other activities, e.g., the control and auditing of measurement points not covered by permanent meters, etc. These portable meters are battery-operated and can be made ready very quickly. Portable clamp-on flow meters are also available in an "energy" and "multifunctional" version, allowing the measurement of thermal energy/BTU flows and making the flow meter the ideal companion for the analysis or auditing of heating and chiller plants [25].

6.2.2 TURBINE FLOW METER APPLICATIONS

Turbine type flow meters with high-quality materials are used in the pharmaceutical industry.

These obviously will be sanitary grade to maintain hygiene. Measurement and control of ultra pure water, air, and liquid flow for pill coating are quite common. The meters to be used must have a very good response time, high accuracy, and repeatability. These are available with an accuracy of around <0.5% AR with repeatability of 0.25% AR or better. Pelton wheel designs are often used. These are available in up to 50 mm sizes.

6.2.3 MASS FLOW METERS

Both Coriolis and thermal mass flow meters are common in these industries. Coriolis meters are found in measurements in pill coating. For gas flow measurements thermal mass flow meters of both types, such as bypass type, as well as immersion types, are used.

6.2.4 SOLID FLOW METERING

Bulk-solids feeders for bulk solids (e.g., powders) are quite common in pharmaceutical industries. Based on the flow characteristics of the bulk materials, the feeder types are selected as discussed in detail in Chapter VIII. Single- or twin-screw feeders, both in volumetric or gravimetric forms, are commonly used for metering bulk solids for milling, granulation, coating, direct compression, and blending. Loss in weight is common in bulk solid processing. Loss-in-weight type feeders are available in a completely encapsulated drive and weighing unit with a removable feeding unit for fast and hygienic cleaning.

6.3.0 Discussions on Flow Meters in Food and Beverage Industries

The food and beverage industries are very wide ranging, and varieties of flow instruments are deployed, but these are used in specialized ways. A short discussion on food and beverage industries in a generalized way has been presented in the following section to start the discussions.

6.3.1 GENERAL PROCESS REQUIREMENTS IN FOOD AND BEVERAGE INDUSTRIES

Utilities in food and beverage manufacturing units, especially in beverage processing, play a very important role. The major benefits include the following:

- Raw water as a major ingredient;
- Clean-in-place (CIP) systems [26];
- Steam generation and process boiler;
- Pollution monitoring (gas and effluent).

Raw water as a main ingredient needs treatments to make it usable and hygienic. This also affects the taste of the beverage. Reverse osmosis (RO) and deionization (DI) are major treatments done on raw water. In this process the flow control of water as well as additives, etc., are important. CIP ensures that all wetted parts remain hygienic and free from contaminants and safe for the manufacturing process. It also protects the system from cross-contamination. Associated with process steam generators are flow measurement of steam, feed water, air, fuel, and flue gas as applicable. The manufacturing process is associated with effluent treatment, and hence flow monitoring of waste water. Measurements of flow in chemical additives are common and PD meters are utilized mainly for these measurements. Blending is also a process normally encountered in beverage manufacturing. Flow meters play an important role in the blending process. Since caustic soda is used for the cleaning operation, ABS as a material of construction is often used in flow meters. Dispensing is an important activity in the beverage manufacturing process. Digmesa sensing technology is mostly used for accurate dispensing. From the above discussions it is clear that there is a wide variety of flow meters in the food and beverage industries. Normally local flow counters are common in flow meters used for the main process. In the following section short discussions on these have been presented to cover various instrument types.

6.3.2 MAJOR FLOW INSTRUMENTS USED

The following are the major instruments normally found in food and beverage industries:

1. **PD meter:** Positive displacement flow meters, measuring volumes of fluid flowing through by counting repeatedly the filling and discharging of known fixed volumes, have been extensively used for adding various ingredients, chemicals, and additives. Reciprocating piston type mechanical units or helical screw principle PD meters are mostly used. Material selections are important, mostly high-grade stainless steel as MOC is used. Normally these instruments have a local counter as well as remote transmission facilities.
2. **Electromagnetic flow meter:** These are deployed for monitoring of the clean in-process fluid's flow and velocity to ensure required turbulence for the cleaning fluids. They are also used sometimes for measurement of ingredients. Full-bore hygienic magnetic flow meters are used to minimize pressure drop and to eliminate the source of cross-contamination. Electromagnetic flow meters are also seen for measurement of ingredient.
3. **Coriolis mass flow meter:** Mass flow meters are frequently used to measure natural gas, fuel, and steam measurements. A Coriolis meter may also be used as a check meter to assure accurate utility billing for natural gases [26]. Since there is not much of a requirement for straight length, Coriolis flow meters are also used for flow measurements of natural gas/steam for accurate accounting purposes.
4. **Thermal mass flow:** Thermal mass flow measurement is used for natural gas flow to process steam generators. Both types of thermal mass flow meters are deployed.
5. **DP type meters:** For measurement of air flow measurement Annubar/Pitot tubes are common in air flow measurements of process steam generators. Similarly, DP meters are also used for measurements of natural gas/fuel flow, as well as steam flow measurements with the help of orifices and other primary elements.
6. **Vortex meter:** For steam flow measurement properly sized vortex flow meters are frequently used for steam flow measurements. Vortex flow meters are also found for measuring RO/DI water flow.
7. **Turbine flow meter:** Axial turbine flow meters using hygienic/sanitary grade materials as MOC are frequently found in food and beverage industries. These are available to cover a wide range of flow, in different spans. Turbine meters are available with very high accuracy and repeatability, as indicated in Table XII/6.1.0-1. Normally these meters are provided with flow conditioners at the inlets. Pelton wheels are also used in place of turbine meters in some applications. In order to meet variations in flow range in batch operations in flow, meters normally support 1.5 times over-ranging facility.
8. **Ultrasonic flow meter:** Both transit type as well as Doppler effect USFMs have been found in food and beverage industries. On account of the nonintrusive and noninvasive characteristics of USFMs, these are the preferred solution for hygienic applications. Also, associated diagnostic features make them unique in food and beverage applications. Digmesa for a dispensing machine can also be based on US technology. A high accuracy of around 0.2% AR is available for these meters.
9. **Solid flow meters:** Loss-in-weight feeders, screw type volumetric, and gravimetric flow meters for measurement of solid flow measurements in food and beverage industries. All these feeders are enclosed types.

Discussion of applications of flow meters in pharmaceutical, food, and beverage industries is concluded and we now investigate the application of flow meters in steel and metal plants.

7.0.0 METALLURGICAL AND MINING INDUSTRIES

Like any other industries, the metallurgical and mining industries have a few specialties in flow meter applications. Metallurgical and mining industries are normally vast process plants. Metallurgical industries, e.g., an integrated steel plant or aluminum plant, covers from mining to final finished products, so vast that almost all kinds of flow meters find their applications in them. Some special application areas of flow metering and/or special flow metering for the metallurgical and mining plants are covered. Also there are good numbers of metallurgical plants to cover metal production of various metals, e.g., Fe, Al, Zn, Cu, etc. This is also applicable to mining industries. Here, as an example, one or two processes are discussed to give an idea about the metallurgical process, so that discussions on flow measurement are meaningful. The discussion starts with process description.

7.1.0 Process Description

As indicated earlier, it is not possible to cover all metallurgical and mining processes. Therefore, a few types of each of these have been discussed here.

7.1.1 INTEGRATED STEEL PLANT PROCESS OUTLINE

The following are the basic steps followed in an integrated steel plant.

1. **Basic raw materials:** Iron ores, coal (coke), and limestone are basic raw materials needed.
2. **Crushing:** The above raw materials are mined and/or brought from nearby and crushed to required sizes.
3. **Stacking and reclaiming:** Crushed iron, coal, and limestone mined or brought from nearby with the help of railway wagons/ships. At the plant these are initially stored with the help of a stacker in piles. Different reclaimer types are used to reclaim the materials from the piles and discharge to different conveyors for delivering the materials to the main plant.
4. **Sinter plant:** Prior to sending iron ore it is sintered at the sintering plant along with limestone and some coke. Here fines are agglomerated into lumps.
5. **Coke oven battery:** Coal is converted to coke in a coke oven battery to remove volatile matter by baking coal in the absence of air.
6. **Blast furnace:** Sintered raw materials, along with coke, are charged at the blast furnace. At the blast furnace, with the help of hot air from stoves, molten iron is produced from the raw materials. A blast furnace (BF) works with the principle of countercurrent gas to solid heat exchange from tuyere raceway to the stock line and of a countercurrent oxygen (O_2) exchange from fusion zone to the stock line. Solid burden materials, such as iron ore, sinter, pellets, coke, and fluxing materials are charged into the top of the furnace, while air normally enriched with O_2, and sometimes with auxiliary fuels, is fed through the tuyeres near the bottom of the furnace.
7. **Steel making (LD furnace):** At the basic oxygen furnace or LD furnace, molten iron is converted to steel with a reduction in carbon content by treatment with oxygen. As a result CO is also produced.
8. **Slab/continuous caster:** At the slab caster or continuous caster, molten steel is slowly rolled and cooled to solid slabs.
9. **Hot rolling:** Slabs are taken to the hot roll mill where they are reheated to bring them to the correct temperature for rolling by passing over a series of rolls to reduce their thickness. Finally, rolled coils of steel are produced for dispatch or may be sent for further thickness reduction.
10. **Cold rolling:** At the cold rolling mill the thickness is further reduced in cold rolling.
11. **Other processes (recycling):** In order to meet the specification, annealing, and galvanizing, etc. are done on the steel. Recycling is another important step. This is done at the electric arc furnace for reusing steel or scrap steel in the making process.

7.1.2 ALUMINUM PRODUCTION PROCESS OUTLINE

Aluminum is produced from its ore, bauxite. Aluminum is produced in an electrolysis process. Apparently the process is simple but in between processing, i.e., preparation of alumina, the smelting process is not so simple as it sounds. Basically there are three major sections in aluminum production:

- Alumina plant for getting alumina from bauxite (Bayer's process);
- Smelter (Hall−Heroult process);
- Captive power generation.

In aluminum production a continuous supply of electrical supply is a must. So, aluminum production plants normally have their own supply of electricity. Also, the amount of electricity necessary will be clear from Table XII/7.1.0-1. For this reason there is the saying "electricity is a major ingredient for aluminum production." Since power generation applications have been discussed already, this part of aluminum production is not described again.

Let us now look into the basic process.

1. **Bauxite to alumina production:** In the refining process alumina is produced from bauxite as per the following steps:
   - *Bauxite grinding:* Extracted aluminum ore bauxite is crushed and mixed with caustic/mother liquor at high temperature and pressure to produce bauxite slurry and red mud.
   - *Predesilication:* Red mud containing undissolved bauxite, sodium aluminate, silicon, and other material traces is put in a settling tank where the mixture gradually settles at the bottom of the tank. Waste materials are removed.
   - *Digestion and dilution:* Bauxite slurry from the tank is pumped into digester vessels for a chemical reaction to dissolve the alumina, maintaining the temperature at around 80−140°C at 3−4 bar pressure. Based on the type of process and ore quality (determined by red mud measurement) caustic soda is added to the slurry. Undissolved particles are removed in the form of water. Finally, sodium aluminate solution is obtained. This is transferred to a settling tank through a series of flash tanks.
   - *Settler washer:* Settling is primarily due to gravity, but chemicals may be added to accelerate settling. The impurities in the slurry, like sand, iron, and other trace elements that do not dissolve, will eventually settle down. The liquor at the top of the tank is passed through filters. Then, after washing, alumina and caustic are recovered and remaining the red mud is dried by evaporation.

TABLE XII/7.1.0-1 Requirements for a kg of Aluminum

Item	Quantity	Remarks
Aluminum	1 kg	1 kg (calculation basis)
Bauxite (Al ore)	4 kg	To produce alumina (1.93 kg)
Aluminum oxide (alumina)	1.93 kg	Required for 1 kg Al production
Carbon	0.415 kg	Required for 1 kg Al production
Aluminum fluoride	0.02 kg	Required for 1 kg Al production
Cryolite	0.002 kg	Required for 1 kg Al production
Electric energy	***>13450 KWH***	Required for 1 kg Al production

Data given here are taken from a large producer of Al: BALCO India. Courtesy: BALCO.

- *Flocculent dosing:* Chemicals are dosed to increase the molecular weight of slurry particles so as to have better settling of slurry particles and enhance the quantity of sodium aluminate.
- *Filtration:* Tiny and fine suspended crystals need to be removed. This is security filtration to remove all impurities. The material caught by the filters, known as filter cake, is washed to recover alumina and caustic soda. The filtered liquor, sodium aluminate solution, is then cooled and pumped into precipitators.
- *Precipitation:* The clear sodium aluminate solution from the settling tank is pumped into the precipitators with the addition of fine particles of "seed crystals" (a kind of alumina) for precipitation. Alumina crystals begin to grow around the seeds and settle at the bottom of the tank for removal to thickening tanks.
- *Calcination:* In order to get anhydrous alumina, aluminum hydrate is calcined at a temperature above 1000°C. Aluminum particles are suspended above a screen by hot air and calcined, which results in producing white powder pure alumina. The caustic soda from the aluminum hydrate produced is recycled into the system.
- *Evaporation and utility section:* This section is meant to reuse caustic soda obtained from various sections in the process. In order to get process steam at various stages, steam generators and a turbogenerator (for power generation) are kept in the alumina plant to meet the needs of the plant.

2. **Smelting and aluminum production:** The Hall−Heroult process of aluminum smelting is basically an electrolysis process comprising a carbon anode and carbon in the base and sides as a cathode. As hydrogen is electrochemically much nobler than aluminum, aluminum cannot be produced by an aqueous electrolytic process. For production of liquid aluminum, an electrolyte (bath) mainly containing cryolite (Na_3AlF_6) is used for electrolytic reduction of alumina (Al_2O_3) to produce aluminum. The other major ingredient used in the smelting operation is carbon. Carbon electrodes transmit the electric current through the electrolyte. Aluminum fluoride is added to lower the melting point of the electrolyte solution. Aluminum is formed at about 900°C, but once formed has a melting point of only 660°C. During the smelting operation, some of the carbon is consumed as it combines with oxygen to form carbon dioxide. As indicated earlier, a huge quantity of electrical energy is required for aluminum smelting. The buildings where the electrolysis cells are located (the *potrooms*) are huge. In a potroom, hundreds of electrolysis cells are arranged in series to form a cell line often referred to as a *potline.* The production process required to produce aluminum is a continuous process. Stopping and restarting of the process is not easy and is always avoided. If production is interrupted by a power supply failure of more than 4 h, the metal in the pots will solidify, often requiring an expensive rebuilding process. For this reason aluminum smelting plants normally have a captive power generation plant to ensure no power interruption.
3. **Captive power plant:** Captive power plants are standard power plants and are already discussed and hence not repeated here.

7.1.3 COAL MINING AND METHANE RECOVERY PROCESS

While on the subject of applications of flow metering in metallurgical and mining industries, coal mining and methane recovery are important places for applications. In this section a process outline of these two processes has been covered.

1. **Coal mining:** There are two basic methods for removal of coal from earth, as described here.
   - *Surface mining:* When the coal is available within around 60 m below the surface, surface mining is used. Giant machineries are used to remove the top layers of soil and rock to expose the coal. After excavation

of coal and mining is complete the soil and rock are returned to fill the mine. After that the entire area should be revegetated**.** There are two type of surface mining: strip mining (area stripping and contour stripping) and auger mining.
- *Underground mining:* Underground mining is used when the coal is buried several hundred meters below the surface or more. Some mines can extend to depths of more than 300 m. Miners use heavy machinery to cut out the coal and rely on conveyor systems to transport the coal to the surface. Some underground mines require elevator shafts to move miners and coal to and from the surface. There are two types of mining methods available here these are: longwall mining and room and pillar mining.

2. **Coal mine methane (CMM):** Methane recovery is another emerging application in coal-mining areas. This is not only an economical proposition but is also gaining attention from environmental pollution prevention also. There are three major sources of coal mine methane (CMM):
   - Degasification systems (drainage) both pre-mine and gob;
   - Ventilation air (VAM);
   - Abandoned or closed mines.
3. **Coal bed methane recovery:** Natural gas, or methane, can be extracted from deep underground in coal beds. CBM is a clean-burning fuel source which is ever-expanding in nowadays. This also helps in moving away from processes that produce high levels of CO_2 emissions to meet environmental regulations.

We now look into the applications of flow metering in metallurgical and mining plants.

7.2.0 Instrumentation Applications in Steel Plants

Right from the sintering plant there are a number of flow measurements involved in the steel making process. Raw material flows to the sinter plant, etc. are measured with the help of solid flow measurement devices such as weigh feeders. Blasts to furnace both cold and hot are important parameters are not only measured by head type flow meters. These flows are controlled also. Clean gas and coke oven gas flow measurement along with steam flow measurements are carried out in the steel making process. Major flow measuring devices and their applications in the steel making process have been described in this section.

7.2.1 DP TYPE FLOW METERING

1. **Blast flow measurement:** At the lower part of the blast furnace, cold or hot blast gases are introduced and these are measured with the help of DP type instruments. For hot blast gas, a flow meter should be installed before the preheaters.
2. **Hot blast flow measurement and PCI (*):** The measurement of flow and safety interlocks for pulverized coal injection (PCI*) is very important for blast furnace operation. The flow measurements can be taken in the blast furnace down leg pipes by installing refractory Venturi tubes. A hot blast air flow system in the straight tubes can be accomplished by DP type flow metering with suitable pressure/temperature compensations. This can be used to accomplish the safety interlocks of the blast furnace with pulverized coal injection (PCI). PCI helps to increase hot metal production and reduce pollution.
3. **Furnace body cooling:** It is an important to check the circulation water flow. A DP type instrument with high reliability and stability is essential.
4. **Oxygen measurement:** It is needless to mention the importance of blast efficiency calculation and ways and means to improve the same. Blast furnace efficiency is greatly influenced by the airflow supplied for combustion. Optimization of combustion can be accomplished by injecting oxygen into the

tuyeres of the furnace. Major criteria for oxygen measurements are listed here:

- Oxygen injection is critical, so metering has to be very accurate;
- To avoid the chances of combustions it has to be clean, safe, and reliable;
- The instrument must be reliable to avoid any downtime.

An integral orifice meter with associated DP transmitter is a good solution [27]. These integral orifice meters should meet international standards like ISO5167 and AGA 3. It is also used for billing purposes by the oxygen plant supplier.

DP meters are also used for oxygen flow to an electric arc furnace. Some are replacing them with vortex meter.

7.2.2 ELECTROMAGNETIC FLOW METER APPLICATIONS

Electromagnetic flow meters are applied for measurement of flow in many applications. The following are only a few examples where normally electromagnetic flow meters are used:

- Tuyere water leakage detection system for a blast furnace;
- Secondary cooling water flow monitoring and control continuous casting machine, i.e., intermittent control and mist spray control [28];
- Hot rolling process: cooling water application in descaling process.

Some distinctive characteristics expected of electromagnetic flow meters are as follows

- The application demands highly reliable magnetic flow meters with diagnostic functions;
- The instrument should be highly accurate and repeatable;
- The instrument must be able to cope up with noise in measurements. In some applications dual-frequency excitation could be a better choice;
- High speed of response is very important in some cases associated with safety.

In order to understand the requirements of the meters mentioned above we now look into the application areas of a few measurements deploying this flow meter type.

1. **Tuyere water leakage detection:** Water is used to cool the tuyeres meant for injection of air into the blast furnace. The differences in flow of cooling water at the inlet and outlet of the cooling circuits is monitored to determine any leak in the cooling circuit. A leak in the cooling water circuit changes the dynamics of the cooling system. This will have an impact on the reaction in the furnace. As a result there will be a decline in furnace performance and efficiency. Also, safety is related with this detection. If the leak is not detected in a timely manner and water is injected into the furnace, hydrogen would be produced, endangering safe operation of the furnace and there will be erosion to the furnace roof and walls. Such a repair is very costly [29]. Leak detection is important for the following reasons:
   - Early detection of leakage, prior to hazard, is essential to improve operational safety;
   - Increased furnace availability by reducing nuisance shutdowns;
   - Reduction in maintenance costs and improved leak detection performance.

   Electromagnetic flow meters in cooling water lines ensure faster and more reliable leak detection, enabling them to avoid critical safety issues and unnecessary shutdowns.
2. **Hot rolling process:** Hot rolling processes involve rolling long heavy thick hot steel slabs into very thin sheets. Descaling the steel throughout the process is an important phenomenon to maintain the desired quality of the sheet. Improper cooling, i.e., inadequate or interruption in the flow of cooling water, can adversely affect the descaling operation. Electromagnetic flow meters are used in these applications to ensure reliable continuous flow measurement in cooling water lines.

7.2.3 OTHER FLOW METER TYPES IN STEEL MAKING APPLICATIONS

There are many other types of flow meters used in steel making plants, some typical applications are as follows:

1. **Turbine and thermal mass flow:** These are normally used to avoid the formation of nitrates within steel manufacturing for developing oxygen-free environment. The argon—oxygen decarburization (AOD) process is used to dilute injected oxygen with argon [30]. Flow meters used are *turbine* type and *thermal mass* flow type flow meters. For better accuracy turbine flow meters are preferred at times.
2. **PD meters:** For measurement of oil flow PD meters are used. Typical applications include but are not limited to: cold rolling oil flow, rust prevention oil, and lubrication application
3. **Vortex:** These are used for measurement of steam flow in the steel making process. Vortex meters are also used for oxygen flow to electric arc furnaces.

We now investigate instrumentation in the aluminum manufacturing process.

7.3.0 Instrumentation Applications in the Aluminum Making Process

Like any other plants there are a number of types of flow meters deployed in aluminum manufacturing plants. These are briefly discussed here. Red mud/bauxite slurry flow is very important and that is where the discussion starts.

7.3.1 APPLICATIONS OF ELECTROMAGNETIC FLOW METERS

The aluminum manufacturing process finds quite good numbers of applications for electromagnetic flow meters, especially in alumina plants. These are as listed here:

1. **Red mud bauxite slurry:** Accurate measurement of the flow of bauxite slurry is very important as this decides the plant output and the efficiency of the entire system. Application of an electromagnetic flow meter for measurements of bauxite slurry, mother liquor flow all these are quite common. Red mud measurement in slurry flow is critical and important, so it has been dealt with at length in Section 4.5.0 of Chapter VII and so is not repeated here.
2. **Some other applications:** In addition to red mud measurements, the following applications also use electromagnetic flow meters.
   - *Digestion and dilution:* Caustic, slurry, chemical dosing, lime flow measurement;
   - *Precipitation:* Prehydrate slurry, seed slurry, and water flow measurement;
   - *Calcination:* Hydrate slurry flow.

7.3.2 APPLICATIONS OF WEDGE FLOW METERS

Wedge flow elements along with multivariable transmitters or DPTs are very suitable for measurement of red mud. A wedge flow element has been discussed at length in Section 5.0.0 (5.3.1) of Chapter VII.

7.3.3 SONAR TYPE FLOW METERING IN ALUMINUM MANUFACTURING

From previous discussions it is clear that this measurement type is the clamp-on type—a nonintrusive, noninvasive instrument type. From discussions in Chapter VII it is also clear that it can measure the volumetric flow and amount of entrained air/gas present in any liquid-continuous-phase process fluid. In aluminum

manufacturing units it is applied on account of the following major features [31]:

- Guaranteed volumetric flow and gas volume fraction;
- Immune to scale build-up;
- Very little maintenance and no down time for installations.

The major application areas include the following:

- Low-temperature digestion feed;
- High-rate decanter feed lines;
- Red mud lines;
- Residue disposal lines;
- Pregnant liquor lines;
- Precipitation slurry lines;
- Seed hydrate lines;
- Product hydrate lines;
- Liquor lines;
- Spent caustic liquor lines;
- Seawater flows.

Apart from these ultrasonic flow meters, compressed air in smelting pots and optical flow meters are also deployed in flow measurements in aluminum manufacturing.

7.4.0 Instrumentation Applications in the Coal Mining Process

There are various kinds of flow measurements involved in coal mining. Management of mining slurry is very important. Nowadays smart mining automations are common, as shown in Fig. XII/7.4.0-1.

Methane gas flow measurement is vital, and the discussions start with this.

7.4.1 METHANE GAS FLOW MEASUREMENT

Methane gas measurement is essential for both CBM and CMM (discussed above). Thermal mass flow meters are used for this purpose. The discussions start with thermal mass flow.

As per regulations, it is necessary that coal mines monitor and report greenhouse gas (GHG) emissions. For CMM the percentage of methane in the extracted gas can be as little as 1% (in VAM processes) to more than 20% in drainage systems. Coal bed methane (CBM) is used as a clean-burning fuel source. Therefore, it is needless to repeat the importance in measuring methane, extracted from deep underground in coal beds. There are various kinds of flow meters used for methane gas flow metering.

1. **Thermal mass flow meter:** A thermal mass flow meter based on thermal dispersion technology, utilizes the relation between flow rate and cooling for direct measurement. This meter does not have any moving parts. Thermal mass flow meters are well suited for gas flow measurement. Available thermal mass flow meters for methane gas measurements are reliable, highly accurate, and repeatable. They are easier to install. These meters are rugged meters with multivariable local LCD readout with the capability to communicate through intelligent means. The meters should be the very fast responding type.

Smart mining Automation: This is a complete automation solution meant to manage mining slurry. This is basically microcontroller (or microprocessor) based automation system to measure and regulate parameters pertinent to mining slurries. These systems use wireless technology to work as "eyes and ears" for management of slurries for allowing a tighter control strategy. Smart mining automation offers the following advantages:

- Accurate flow measurement and control accuracy
- Extended life for measuring and control devices
- Advanced diagnostic features

FIGURE XII/7.4.0-1 Smart mining automation.

2. **Turbine flow meter:** Turbine flow meters are used for measuring flow of methane gas, with a high accuracy of around 0.1% and high turndown. However, it has moving parts.
3. **Vortex flow meter:** Vortex meters are used for the measurement of methane gas. They are available in insertion types. These meters are available with an accuracy of around 1% AR. For further details Section 9.2.0 may be referenced.

7.4.2 MINE WATER FLOW MEASUREMENT

Normal mine water flows are through an open channel. These could be in rectangular concrete channel, partially filled channel, brown coal purification water flow, and flow of water with high solid contents. Based on the open channel type, an empirical formula is utilized to measure the differential level by ultrasonic or other means of level measurement as detailed in Chapter III (for US level sensing refer to Section 4.1.5).

7.4.3 MEASUREMENT OF FEED FLOW TO HYDROCYCLONES

Hydrocyclones are used for the classification of particles in slurries. The particle size of the cyclone feed slurry ranges from 250 to 1500 μm, leading to high abrasion. The particles cause a high slurry noise, so well-responsive, reliable, and highly accurate measurement is very challenging. Also, the meter has to be of low maintenance, even after withstanding so much abrasive wear. Electromagnetic flow meters with a ceramic carbide liner and tungsten carbide electrodes could meet these needs as seen previously. Electromagnetic waves with double-frequency excitation would be better to maintain a higher signal to noise ratio. Some electromagnetic flow meters in this application are found to have a protection ring at the inlet of the flow meter to increase service life of the sensor, protecting the liner material from abrasion due to differences in the inner diameter of the flow meter and the connected pipe. It is recommended to install the associated transmitter/electronics away from the meter, i.e., remote electronics are preferred to avoid effects due to vibration.

After completing the discussions on the application of flow instruments in metallurgical and mining industries, we investigate the application of instrumentation in cement industries.

8.0.0 FLOW MEASUREMENTS IN CEMENT PLANTS

Cement, the basic ingredient of construction, is critical because only it has the ability to enhance the viscosity of concrete, which in returns provides the better locking of sand and gravels together in a concrete mix. Portland cement can be manufactured in two different processes: a dry process and a wet process. The basic ingredients of both types are the same. Limestone, shells, chalk, shale, clay, slate, silica sand, and iron ore are the main ingredients for cement manufacturing. Of these, lime and silica make up nearly 85% by mass of Portland cement. Therefore, cement plants are normally located near limestone quarries. Basic raw material handling in dry and wet cement plants are similar. In the case of wet cement plants, water is added with the raw materials mentioned above. Another difference is that in the case of the wet system raw meal in the form of slurry is introduced into the kiln, whereas in the dry process dry meal is placed into the kiln system. The wet process is obsolete and dry processes are now mostly in use. In the following the dry cement making system has been discussed in brief. The process details given here are generalized in nature. There may be some variations with different designs.

8.1.0 Brief Cement Making Process

The following are the basic steps for the cement manufacturing process:

1. **Quarry:** Basic raw materials, e.g., limestone, are mined and sent to the plant for crushing;

2. **Crushing:** Here big lumps of mined materials are crushed into smaller pieces for stacking;
3. **Stacking and reclaiming:** All raw materials such as limestone, shale, coal, etc. in smaller pieces are stacked (may be in an open place). During operation the materials are reclaimed by a suitable reclaimer for sending to a raw mill;
4. **Raw mill:** In the raw mill, which can be of different design, such as a roller press or ball tube type, for grinding the raw materials into fines suitable for pneumatic conveying;
5. **Blending and storage silo:** Before entry to raw mills, various ingredients in due proportions are discharged from different bins with the help of a set of conveyors with a weighing arrangement for regulated flow of raw materials. Proper blending is done at the blending silo with the help of air flow in the silo;
6. **Kiln feed:** Raw meal to be charged to the kiln through a preheater series are weighed properly to regulate the flow to the kiln;
7. **Preheater:** There is a series of preheaters (cyclone) associated with where raw meal is preheated (and may be precalcined also) prior to feeding the materials to the kiln. This is actually a heat transfer area where solid raw meal is heated by the gas coming out of kiln due to firing and reaction. In some installations there would be precalcinator also associated with preheater precalcinations of the raw meal prior to charging to the kiln. Basically the preheater is a part of the kiln;
8. **Kiln with firing, secondary, and tertiary air:** It is the place where the actual chemical reaction takes place for clinker formation. Details about the reaction are not yet well defined. Kiln firing is done with the help of a suitable burner design, which may vary with the supplier's design. Oil and/or coal are used as the fuel for combustion. Air systems are:
   - *Primary air:* This is the air from the blower that goes directly to the kiln, primarily to bring the coal powder into the kiln and/or flame adjustments. Therefore, primary air is necessary for all types of burner
   - *Secondary air:* This is the air from the grate cooler that goes directly into the kiln, i.e., it flows from the kiln head to the tail. It is the main air necessary for combustion
   - *Tertiary air:* This is the air from the grate cooler, which bypasses the kiln and goes to the preheater/precalcinator to support combustion in the decomposing furnace through the tertiary pipes;
9. **Clinker cooler:** Clinkers formed in the kiln are discharged to the clinker cooler, below which air is blown by a fan/blower to cool the clinkers. This is the clinker cooler. From the clinker cooler, cold (tempered) coolers are sent for the clinker silo;
10. **Clinker storage:** This is the place where clinker is stored for subsequent use in the cement mill;
11. **Clinker grinding and additive:** Clinker from the clinker silo is taken for grinding in the cement mill; normally ball mills are mostly used for this purpose. During the grinding process additives like gypsum, prozolona, etc. are added for cement making;
12. **Cement silo:** Cement produced in the cement mill is conveyed to the cement silo after passing through separators, etc. The cement silo is the storage place for ground cement;
13. **Dispatch and packing:** Cement is sold in the market in bags. Cement is also dispatched in trucks. There are many kinds of packing/bagging machine designs available;
14. **Utilities:** There are many utilities normally found in cement plants. These are coal handling and storage systems, oil handling systems. Nowadays for the heat recovery process, boilers and power generation units are also incorporated within the plant as another utility.

Since there are silos in between, it is not necessary that the raw mill and/or cement mill has to run when the kiln is in operation. This indicates that this is a noncontinuous process.

Clinker production is a very energy-intensive activity. Nearly 65%−70% of total variable costs are due to spending on energy. Therefore, it is needless to say that choosing fuels, the right blend of hot gases, and optimum burner control, along with cogeneration are of immense importance. In view of this, the following controls are very important and effective:

- *Kiln burner control* and fuel injection;
- *Clinker cooler* package;
- *Cyclone preheater and precalcinator* control;
- *Cogeneration* (as applicable).

In all such cases flow measurements play a major role. Various kinds of solid flow measurement systems discussed in Chapter VIII are mainly deployed in this plant to account for various flows. We now look into some of these specialties.

8.2.0 Flow Measurement Specialties in Cement Plants

8.2.1 AIR FLOW MEASUREMENT BY TRIBO ELECTRIC METHOD

Measurement of air flow is necessary for proper operation of the plant. However, major difficulties arise on account of heavy dust concentration in the medium. Typical such applications in air flows are for the following cases:

- Raw mill exhaust;
- Primary air;
- Secondary air (air from grate cooler);
- Tertiary air;
- Air flow from the cement mill.

Various issues related to measurement of gas flow laden with dust have been discussed in Section 1.1.0 above. Apart from these there are a few methods for air flow measurements by deploying tribo-electric principles. Each particle has a static charge associated with it. Each measurement requires two sensors located a defined distance apart. The sensors obtain a millivolt pattern from the passing particles. Each of the sensors obtains a similar pattern. With the help of a computer correlation is established between the sets of sensors. The velocity is the average over the effective length used in the computer for flow measurement, similar to what has been discussed in Section 2.2.3 above. A similar system has been used in Shree Cement in India for plant optimization by The MECONTROL Air system.

8.2.2 ROTARY WEIGH/GRAVIMETRIC FEEDER

The rotary weigh/gravimetric feeder has been discussed in Sections 3.1.1−3.1.3 in Chapter VIII. In cement plants these can be used in limestone and coal/coke flow measurements. The following are the major advantages:

- Highly reliable system with long life;
- Online calibration is possible when pre bin is with load cell;
- Withstand heavy pressure fluctuations;
- Easier maintenance [32];
- High accuracy in a wide flow range from 10% to 100% flow rate [32].

These are used for feeding and dosing control. They find their applications in the kiln process, grinding process, and mill residue to the cement mill.

8.2.3 MASS FLOW MEASUREMENT OF CEMENT FOR REDUCED CHROMATIC CONCRETE

In order to reduce the risk of skin-related illnesses, in the case the somebody comes in contact with fresh concrete, there is an EU directive for the reduction of chromatic concrete. Mixing iron-sulfate to the cement production process limits chrome-VI to 2 ppm or less and circumvents the risk related to skin disease. Iron-sulfate is added to cement before it goes to the bag packaging area. Iron-sulfate dosing is done precisely, at around 0.5% of mass for best results [33]. It is necessary to measure the mass flow so that an accurate amount of iron-sulfate dosing can be calculated on line and can be added. Based on the Semrad document a typical such arrangement has been detailed in Fig. XII/8.2.0-1 (courtesy: Semrad).

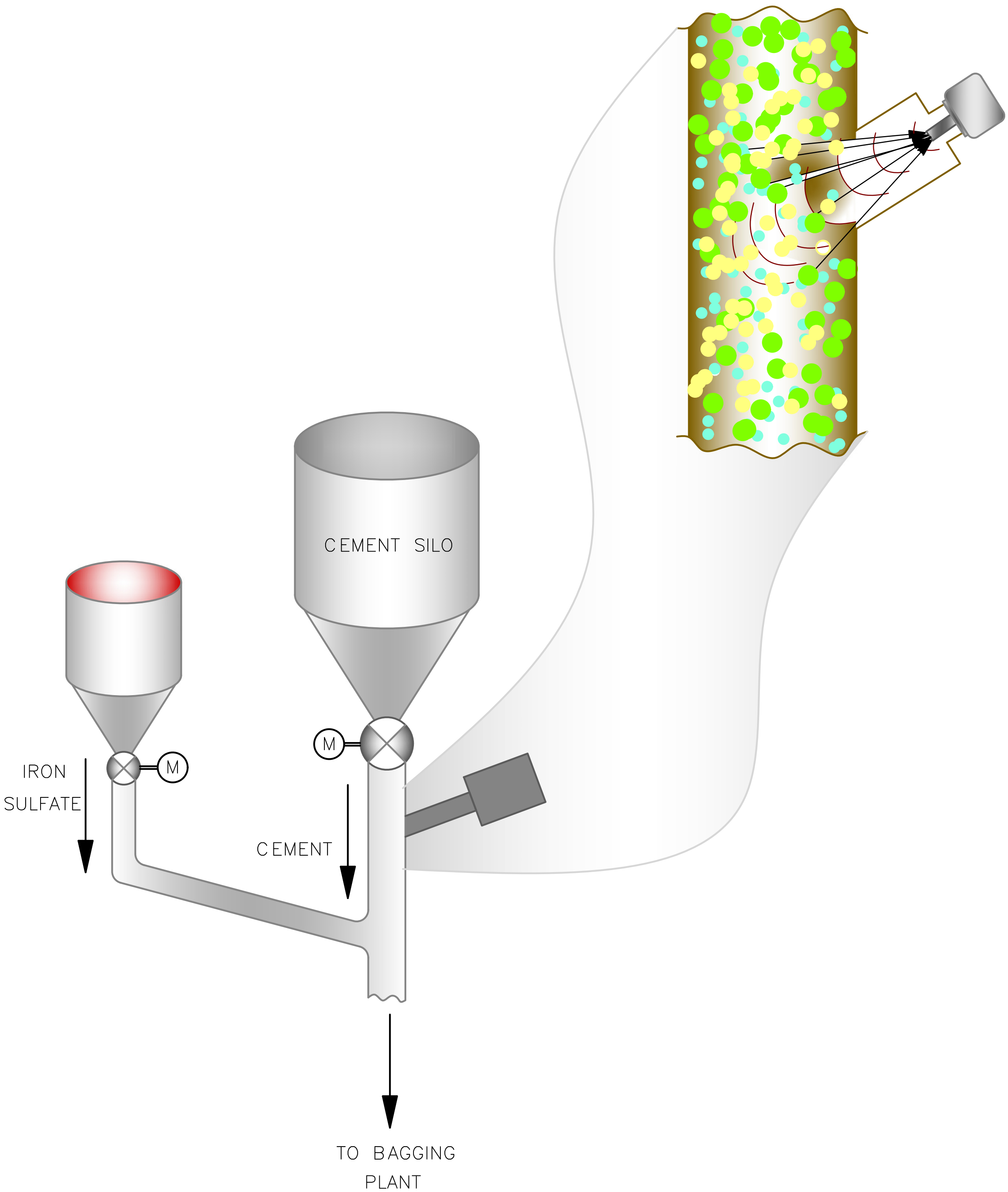

FIGURE XII/8.2.0-1 Iron-sulfate dosing and mass flow measurement. For detailing refer to Fig. I/3.2.3-1. *Developed based on an idea from Mass Flow Measurement on Cement at Lafarge Perlmooser GmbH, Application Report Mass Flow Meter MF3000 for Solids, Semrad, NSW. http://www.semrad.com.au/images/Articles/Impact_Weigher_Alternatives/Case_Study_Flow_Meter_For_Cement_Plant.pdf. Courtesy: Semrad.*

As result of this one gets the following advantages also:

- On-line cement mass flow for bagging measurement;
- Optimized mixing of iron-sulfate to achieve regulated limits;
- Less iron-sulfate is required for the process [33].

The measurement is carried out by noncontact microwave technology discussed in Chapter VIII. On account of the following reasons microwave technology is chosen for mass flow measurement:

1. Noncontact on-line measurement of mass flow;
2. No weighing system involved;
3. Installed flush to inner wall, hence nonintrusive;
4. Simple welding to the pipe easy installation and setup;
5. Microwave is very suitable for free-fall applications with pneumatic conveying;
6. Available with various outputs (refer to Chapter VIII);
7. Simple, low-cost installation and start-up [33].

With this, the discussion on flow meter applications in cement plants comes to an end and we now investigate a few other applications in different plants.

9.0.0 FLOW MEASUREMENTS IN MISCELLANEOUS PLANTS

In Section 1.0.0 flow applications and general issues common to many plants have been elaborated on. In Sections 2.0.0–8.0.0 specific issues and processes of specific plants and industries have been outlined. Apart from these, there will be many other plant types in existence. Although it is not possible to cover them all, some attempts have been made to include flow-related issues for these plants. Ethanol plants are popular and the discussions start with ethanol plant flow issues.

9.1.0 Flow Measurements in Ethanol Plants

9.1.1 ETHANOL PRODUCTION PROCESS

Ethanol, which is same as ethyl alcohol, now finds industrial applications as well as a fuel. In the US it is mainly used as a fuel. The first automobile to completely use ethanol was manufactured in 1978 in Brazil.

Major steps for manufacturing (dry mill) ethanol include the following:

1. Milling;
2. Liquefaction;
3. Saccharification;
4. Fermentation;
5. Distillation;
6. Dehydration;
7. Denaturing.

There are a few byproducts available during the above process. During the process of conversion of corn into fuel ethanol, there is need for automation of production optimization. There is a need for flow controls in this process. Also, the process finds use various types of flow meters. Some of these are discussed in this section.

9.1.2 FLOW METER TYPES AND SELECTIONS

A wide range of flow meters are used in this process for measurements of the speed, volume, and mass of slurries, liquids, and gases in pipelines. Major flow measuring fluids are: beer, stillage, syrup, enzymes, water, steam, CO_2, and natural gas, as well as methane that is used as an alternate fuel [34].

1. **Flow meter types:** There is a wide variety of flow metering devices and technology available for flow measurement purposes. These include but are not limited to the following:
   - Electromagnetic flow meter;
   - Ultrasonic flow meter;
   - Vortex meter;
   - DP type meter;

- Variable-area flow meter;
- Coriolis mass flow meter;
- Thermal mass flow meter.

2. **Flow meter selection:** Of the various types of flow meter discussed, for different applications flow meters are selected on the basis of the following selection criteria:
   - Accuracy and repeatability of the measuring technology;
   - Requirement for temperature compensation and arrangement for compensated flow measurement with desired accuracy and repeatability;
   - Calibration matched to specific applications;
   - Wide turndown for accurate low and high flow rate measuring;
   - Multipoint sensing for large pipes, stacks, and ducts as required, with desired accuracy;
   - Ease to install the meter;
   - Cost-effectiveness;
   - Flow conditioning for limited straight-run applications.

9.1.3 FLOW METER APPLICATIONS

1. **Coriolis meter:** During production, in order to reduce flow problems and enzyme usage and other costs, real-time measurement and control are necessary. This allows more consistency in the slurry mix solids and enables operators to push the solids percentage higher [34]. For continuous monitoring of solids concentration, Coriolis meters can be used to get high accuracy and repeatability in density measurements. The use of an on-line flow/density meter at the intermediate and final stages of the evaporator process helps in significant reductions in energy consumption for an evaporator. Coriolis mass flow meters can also be used for steam flow consumption.
2. **Magnetic flow meter:** Upstream of fermentation there is extensive use of in-line electromagnetic flow meters to measure flows with high solids content, e.g., corn slurry, mash, beer, as well as on whole, thick, and thin stillage [34]. As mentioned in Chapter V, electromagnetic flow meters are applied with due consideration towards performance limitations of pulsed DC type in noisy slurry applications. Therefore, meters with self-diagnostic capabilities for detecting sensor-coating degradation and predicting electrode or liner failure will be important in making the selection.
3. **Thermal mass flow meters:** Thermal mass flow meters are used to measure air flow and fuel flow for optimization of the combustion control of process heaters such as distillation tanks. Also, thermal flow meters can be used to measure the CO_2 leaving the fermentation tanks and for steam consumption measurement as indicated below.
4. **Vortex mass flow and DP measurement:** For measurement of steam flow used in cooking, dehydration, and evaporation, a vortex meter or DP meter can be used. However, these are volumetric measurements for mass calculations, and necessary compensation and flow computation would be essential. Saturated steam flow measurement by these could be problematic, so Coriolis and thermal mass flow meters can be used.
5. **Turbine meter:** The turbine flow meter offers an accurate, compact, and economical solution for ethanol splash blending. The meter is easily incorporated into the blending stand equipment.
6. **Miscellaneous meter types:** Where there is an issue with low conductivity, such as downstream of the rectification process, DP type, turbine type, vortex type, or USFM type flow meters can be applied. The turbine type, on account of moving parts, may pose problems like mechanical failure and problems due to coating.

9.2.0 Energy Consumption in Biogas

In this section brief discussions are given on flow measurement of safe, clean, low biogas—greenhouse gas (GHG), landfill gas (LFG), and coal mine methane (CMM). The basic purpose of these metering systems is to account for energy

provided by fueling with the various gases mentioned above. Energy consumption metering systems consist of a methane analyzer to measure the methane content of the gas supply by volume. Therefore, in order to accomplish this it is necessary to measure the flow of gas. A gas meter, like a swirl meter, can be installed to note the volumetric flow rate and by measuring pressure and temperature downstream of the flow meter, it is possible to get the mass flow. Associated with this a flow computer is utilized to perform the required calculations for total consumption in energy units [35].

9.2.1 METER DETAILS

As indicated in Subsection 7.4.1.3, vortex/swirl meters can measure the actual volume flow rate of LFG, CMM, and other biogases, independent of composition, with a high accuracy of ±0.5% or better for a wide range of flow. There is a specialized meter using proprietary technology [35: courtesy: ABB] that can be used also. These meters meet high accuracy in wide flow range and are not influenced by external factors. They can communicate with dedicated computers for energy consumption measurement in various forms of electrical output types, e.g., analog/pulse output as mentioned in Chapter V.

9.2.2 MEASUREMENT REQUIREMENTS AND CONSTRAINTS

The following are the basic measurement requirements:

- Low-pressure volumetric flow measurement of biogas;
- Very limited up- and downstream pipe diameters;
- Requirements of consistent accuracy and repeatability over the flow range even at the lower end;
- Ability for pressure and temperature compensation for mass flow computation;
- Suitability of meter design for hazardous applications;
- Availability of meters in various sizes.

9.3.0 Heat Consumption Measurements for Centralized Steam Supply

There are many industrial parks, housing societies, commercial complexes, and shopping malls, etc., where there is a needs for steam and heat supplies for a number of uses from a centralized steam generator. Quite often these are either supplied from the municipality and/or from an external agency, which generates the steam from a centralized steam generator (SG) at a nearby place and it is then distributed to subscribers through insulated pipelines. This is applicable for any integrated plant where there may be different plants with separate profit centers which also receive steam from a centralized SG. In all these cases there is a need to account for the consumptions for billing purposes. Naturally the measurement of heat (from steam) accurately must be recorded by taking a variety of individual measurements. In order to measure heat it is necessary to monitor not only steam flow but also the pressure and temperature of steam supplies. With seasonal variations (winter and summer), high and low consumption patterns are noted. As a result of these there may be two sets of flow measurements with different nominal diameters often required for accurate energy flow measurement for billing purposes, as at the lower end (during summer) the required accuracy may not be achievable with a single metering system. The installation of two devices with graded nominal diameters is recommended for measuring points where fluctuations in consumption are so great that the measurement dynamics of one device are no longer sufficient [36]. In these applications vortex/swirl meters can be applied. Vortex/swirl meters can be used along with pressure/temperature measurement for heat calculations through computers. There are swirl/vortex meters which can be used in split range mode for switching (adjusting) between these flow ranges.

9.4.0 Flow Measurements in Breweries

In a typical brewery, e.g., for beer manufacturing, the main issue is to extract sugar from grains

so that yeast can convert into alcohol with CO_2 as waste byproduct.

9.4.1 BREWING PROCESS

The major ingredients are barley, hops (a green cone-like fruit of a vine plant), water, and yeast. Ingredients for other spirits and alcohol manufacturing processes may be different, but a basic outline of the process has been described below. It is worth noting that in the brewing process practically everything flows. Naturally there is a wide range of applications of flow meters and flow meter types.

1. **Malting:** The harvested grains are processed through heating, drying out, and cracking for malting by isolating the enzymes for brewing.
2. **Mashing:** At this stage the grains are steeped (softening and extracting constituents) in hot, but not boiling, water for about an hour so that grains break down to release sugars. Excess water is drained to obtain a sticky, sweet liquid, which is called *wort*.
3. **Boiling and additives:** The wort is boiled for about an hour and hops and other spices are added to remove sweetness and give bitterness. These additives also act as preservatives.
4. **Cooling process:** After an hour-long boiling the wort is cooled, strained, and filtered.
5. **Fermentation:** After filtration, it is put into a fermenting vessel with yeast added to it for fermentation to begin. The beer is stored for a couple of weeks at room temperature. During fermentation, the yeast eats up all the sugar in the wort and gives out alcohol and CO_2 as a waste byproduct. There are many some variations in timing and temperature for lagers, etc.

9.4.2 FLOW METERING IN THE BREWING PROCESS

Flow monitoring is essential for breweries because flow monitoring can provide information on operational errors or issues such as leaks or blockages, etc. Also, such monitoring allows for quick action to be taken to resolve the issue and in turn this reduces waste. As such, energy balance and energy optimization are possible only through suitable monitoring of flow at different points in breweries. The benefits achieved by flow monitoring can impact on process management, the production of reports, and ultimately profits. As stated earlier, in the brewing process there is good scope of applications of flow meters. Mostly in-line type and clamp-on type meters are used in breweries. Electromagnetic, turbine, Coriolis, vortex/swirl, and USFM types are used in breweries. In this section short discussions will be given on these flow meters.

1. **Turbine meters:** Turbine type flow meters are quite common in flow measurements in brewery applications. Typical triclamp process connections, which allow easy installation and removal, are quite common in most breweries. In order to circumvent upstream and downstream straight length requirements, many of these meters use flow conditioners also. The stainless steel construction meets chemical compatibility of all liquids used in the brewing process, including water, and sterilization or cleaning chemicals. These are available with external power and outputs. These meters offer good accuracy in the tune of 1% AR. They are available in low-cost versions with slightly lower accuracies. These meters are available in different sizes to cater to the requirements of breweries. They also have built-in display/indication for both total volume and flow rate.
2. **Electromagnetic flow meter:** Breweries also use electromagnetic flow meters in those applications when conductivity of the fluids above the minimum value are required. Like turbine flow meters these are available in different sizes to meet the demands of brewing applications. In applications it has been found to be an ideal solution for supplying information on the measurement and tracking of beer through the brewing process. These meters are without any moving parts with very low pressure loss in the system. These flow meters can be used to track the entire system with good accuracies for measurements. Electromagnetic flow meters are frequently used for automatic transfer operations as well as in wine and juice flow measurements.

3. **Vortex/swirl meter:** Since the process involves heating by steam, naturally vortex/swirl meters find good applications in this process. In order to increase temperature of steam heating, suitable controls are used. The steam flow from the steam header is measured and controlled with a control valve. The steam flows in these lines are typically monitored and regulated with the help of vortex/swirl flow meters. One of the most favorable characteristics for vortex meters over other types of meters is the minimal upstream and downstream straight pipe requirements. Also, with measurements of pressure and temperature downstream of the meter mass flow, energy computations are easier.
4. **Ultrasonic flow meter:** Globally, brewing plants use noninvasive ultrasonic flow meters. These are very suitable for retrofitting as well as greenfield projects. They are not only used for day-to-day monitoring, but are often used to demonstrate the performance of inspection parameters. As they are noninvasive, they minimize the risk of contamination, in addition to minimizing damage to the flow meter and disruption when the devices are installed and maintained. Typical and major applications include the measurement of thermal energy flow rates in mash containers, measurement of the cooling capacity of wort coolers, etc. Wherever mass flows need to be computed, they are done with the help of the temperature difference between the media intake and the discharge of the thermal energy flow. They accurately monitor the flow rate and display data on a screen. The major advantages of USFM are listed here:
   - *Noninvasive:* These are noninvasive flow and thermal measurements and it is easy to set-up measuring points very quickly.
   - *Hygienic:* As they are noninvasive, they are very hygienic, minimizing the chances of any contamination. Hence they are perfectly safe.
   - *Totalizer:* An integrated totalizer of the meter allows it to be used as an energy meter.
   - *Flexibility:* USFMs offer maximum flexibility for the measuring system and are easily adjustable. Also, a single unit can perform several tasks.
   - *Diagnostics:* USFMs normally have diagnostic features built in to make them versatile.
5. **Coriolis mass flow meter:** Mass flow is important for energy balance. Therefore, Coriolis mass flow meters, which are not disturbed due to profile deformations, are always preferable solutions. These meters also offer high accuracy. As noted earlier, cost and pressure loss are the only factors which limit their applications. These meters are available with various communication facilities so they can be integrated together to form a computer network for brewing process monitoring,

   The discussions on applications of flow meters in various processes including a few examples have been covered. There are many other applications, be they domestic, industrial, or commercial. Frankly speaking, there are hardly any plants which do not require flow measurement. We conclude the discussions with these application notes.

With this the main discussions on plant flow measurement and control have been concluded. To supplement the discussions presented in the main chapters additional pertinent information is provided in the appendices to look into:

Appendix I: Unit Conversion and Flow Regime;
Appendix II: Material Selection Guide;
Appendix III: Mechanical and Piping Data;
Appendix IV: Custody Transfer;
Appendix V: Safety Life Cycle Discussions;
Appendix VI: Enclosure Electrical Protection;
Appendix VII: Device Communication.

I would be more than happy to share my experiences with the reader. This will bring fruitful results **only** when it could be utilized in some of the issues people are facing day to day in their plants. Any good suggestions are always welcomed.

LIST OF ABBREVIATIONS

ABS Absolute
AC Alternating current
ADC Analog-to-digital converter
AI Analog input
AO Analog output
AR Actual reading (in connection with accuracy)
CCW(CW) Counterclockwise (Clockwise)
CEP Condensate extraction pump
CMRR Common mode rejection ratio
CMV Common mode voltage
COC Change over contact
CPU Condensate polishing unit
CS Carbon steel
CV Calorific value/control valve
DAS Data acquisition system
DC Direct current
DCS Digital control system
DI Ductile iron/digital input
DO Digital output
DP Differential pressure
DPT Differential pressure transmitter/transducer
DSP Digital signal processing
EMC Electromagnetic compatibility
EMI Electromagnetic interference
FC Fail to close (for valve)
FO Fail to open (for valve)
FRP Fiber glass reinforced plastic
FSD Full-scale division (of calibrated span) (in connection with accuracy)
HC Hydrocarbon
HVAC Heating, ventilation, and air conditioning
IC Integrated chip/internal combustion (engine)
ID Internal diameter
I/O Input/output
I/P Current to pneumatic converter
IS Intrinsic safety
LCD Liquid crystal display
LED Light-emitting diode
LHS Left-hand side
LRL Lower range limit
LVM Limit value monitor
MS Mild steel (main steam)
MUX Multiplexer
MVT Multivariable transmitter
NB Nominal bore
NIST National Institute of Standards and Technology
OD Outer diameter
PLC Programmable logic controller
PD Positive displacement
PT Pressure transmitter or pressure temperature (P/T)
PTFE Polytetrafluoroethylene
PU Processing unit
PVC Polyvinyl chloride
PVT Pressure volume temperature
RF Raised face/radio frequency
RHS Right-hand side
RPM Revolutions per minute
RTD Resistance temperature detector
SG Specific gravity/steam generator
SIL Safety integrity level
SPDT Single-pole double-throw
SPST Single-pole single-throw
SS Stainless steel
STP Standard temperature and pressure (Fig. I/1.1.2-3)
TD Turndown
TC Thermocouple
URL Upper range limit
US Ultrasonic/United States
USFM Ultrasonic flow meter
VDU Visual display unit
VFD Variable-frequency drive
VM Valve manifold
W/O Without/water in oil (emulsion)
WRT With respect to

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APPENDIX I

UNIT CONVERSIONS AND FLOW PROPERTIES

In this appendix various unit conversions for commonly used parameters pertinent to flow measurements have been covered. For important fluids *density and viscosities* have been indicated in tabular forms at specified temperatures. Also, this appendix includes various flow regimes and profile changes based on Reynolds number. The discussions start with unit conversions.

1.0.0 UNIT CONVERSIONS

Unit conversions of pressure, temperature, density, length, viscosity, volume, mass, and flow units have been elaborated. Units are expressed with standard abbreviations. Appendix III may be referenced for unit conversions pertinent to force, torque, power, time, and energy.

1.1.0 Pressure Conversions

Prior to going for conversion it is better to get details about various explanations for pressure types normally encountered in process plants and used in various flow element sizing calculations.

1.1.1 EXPLANATION OF PRESSURE AND VARIOUS DEFINITIONS

The following are detailed explanations of various pressure terms:

1. **Absolute pressure:** This refers to zero-referenced against a perfect/absolute vacuum, i.e., absolute zero pressure (or no force).
2. **Absolute pressure at a point:** This is the actual pressure at a given point and is called the absolute pressure when it is measured relative to an absolute vacuum.
3. **Gage pressure at a point:** Gage pressure at a point is the pressure relative to the atmospheric pressure, i.e., it is relative to atmospheric pressure or in other words indicates how much the pressure is above or below atmospheric pressure.
4. **Vacuum pressure:** Vacuum pressure represents pressures below atmospheric pressure and expressed in terms in absolute pressure. Normally it indicates the difference between the atmospheric pressure and the absolute pressure. It will be clear from an example: Condenser vacuum 0.1 kg/cm^2A means that at the condenser pressure is 0.1 kg/cm^2A.
5. **Draft:** Basically this is the similar to a vacuum, but when it is indicated with respect to atmospheric pressure it is referred to as draft. It will be clear from an example: Furnace draft (−)3″ wcl means that at the furnace, pressure is *less than* atmospheric pressure by a pressure equivalent to force exerted by 3″ of water column at 68°F on unit area (in sq. inch).
6. **Atmospheric pressure:** The atmospheric pressure is the pressure that a unit area experiences due to the force exerted by the atmosphere.
7. **Transfer equations:** From these it is clear that gage pressure (P_{gage}) will be absolute pressure (P_{abs}) minus atmospheric pressure (P_{atm}):

$$P_{gage} = P_{abs} - P_{atm} \qquad \text{(AI/1.1.0-1)}$$

Vacuum (P_{vac}) will be the absolute pressure (P_{abs}) less than atmospheric pressure (P_{atm}):

$$P_{vac} = P_{atm} - P_{abs} \qquad (AI/1.1.0\text{-}2)$$

Absolute pressure (P_{abs}) will be gage pressure (P_{gage}) plus atmospheric pressure (P_{atm}):

$$P_{abs} = P_{gage} + P_{atm} \qquad (AI/1.1.0\text{-}3)$$

These are explained in Fig. AI/1.1.0-1.

Conversion factors of pressure into various units have been elaborated in Table AI/1.1.0-1.

1.2.0 Temperature Conversion Factors

Temperature unit conversion factors for commonly used temperature scales have been indicated in Table AI/1.2.0-1.

1.3.0 Volume and Mass Conversion Factor

1.3.1 VOLUME CONVERSION FACTOR

Volume unit conversion factors for commonly used volume-measuring scales have been indicated in Table AI/1.3.0-1.

TABLE AI/1.1.0-1 Pressure Unit Conversion Factors (mmwcl = 0.1 mbar)

atm	bar	kg/cm^2	K Pascal	psi	mmwcl	Inch Hg	Torr
1	1.01325	1.033227	101.325	14.69595	10132.5	29.9216	760
0.986923	**1**	1.0176	100	14.50377	10000	29.5299	750.0617
0.967842	0.982704	**1**	98.0665	14.22334	9806.65	28.95903	735.5592
0.009869	0.01	0.010197	**1**	0.145034	100	0.295299	7.500617
0.068046	0.068948	0.070307	6.894949	**1**	689.4757	2.036021	51.7493
9.87E−05	0.0001	0.000102	0.01	0.00145	**1**	0.02953	0.750062
0.033421	0.033864	0.034532	3.386398	0.491154	33.86388	**1**	25.4
0.001316	0.001333	0.00136	0.133322	0.019324	1.333224	0.03937	**1**

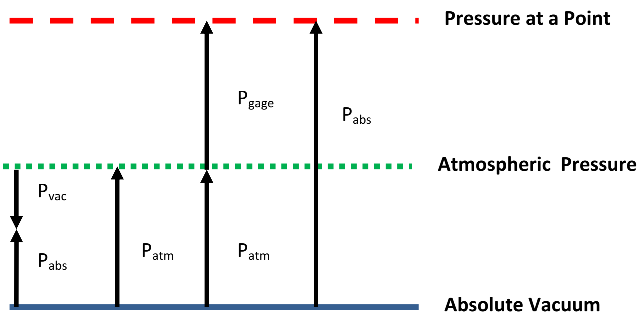

FIGURE AI/1.1.0-1 Pressure definitions.

TABLE AI/1.2.0-1 Temperature Unit Conversion Factors

Celsius	Fahrenheit	Kelvin	Rankin
1	33.8	247.15	493.47
0.0295858	**1**	255.9278	450.67
0.00404613	0.00390735	**1**	1.8
0.00202647	0.00221892	0.5555556	**1**

TABLE AI/1.3.0-1 Volume Unit Conversion Factors

cc	cft	CubMt	gal	gal (UK)	Ounce	Pint	Liter
1	3.53E−05	1.00E−06	0.000264	0.00022	0.0338	0.00211	0.001
2.83E+04	**1**	0.02832	7.48051	6.2288	957.91	59.8441	28.3168
1.00E+06	35.3157	**1**	264.1721	219.9692	33,814	2113.39	1000
3786.445	0.13368	0.00379	**1**	0.83267	128		3.7854
4546.095	0.16054	0.00455	1.200956	**1**	153.72	9.6076	4.556
29.57355	0.00104	2.96E−05	0.007813	0.006505	**1**	0.0625	0.02957
473.1936	0.01671	0.00047	0.125	0.104084	16	**1**	0.4731
1000	0.03531	0.001	0.264173	0.219491	33.818	2.11372	**1**

Barrel Unit for oil: 1 ***Barrel*** = 42 US gal; =158.94 L/0.159 m^3.

1.3.2 MASS CONVERSION FACTOR

Conversion factors for mass unit have been elaborated in Table AI/1.3.0-2.

1.4.0 Density (Specific gravity) and Viscosity Conversion Factors

1.4.1 DENSITY UNIT CONVERSION FACTORS

Density unit conversion factors have been enumerated in Table AI/1.4.0-1.

1.4.2 DENSITY SPECIFIC GRAVITY OF A FEW SELECTED MATERIALS

Specific gravity of a few selected liquid and gaseous materials have been enumerated.

Table AI/1.4.0-2 Specific Gravity of Selected Materials.

The specific gravities for liquids at 20°C have been indicated here. The density of gases is computed at °C at 1 atm pressure. The specific gravities of liquids are based on the density of

TABLE AI/1.3.0-2 Mass Unit Conversion Factors

Gal H_2O @32°F	kg	lb	Metric ton	Ton
1	3.785	8.345	0.003786	0.003726
0.264201	**1**	2.205	0.001	0.000984
0.119832	0.453515	**1**	0.000454	0.000446
264.131	1000	2204.586	**1**	0.9842
268.3843	1016.26	2240.143	1.016054	**1**

TABLE AI/1.4.0-1 Density Unit Conversion Factors

g/cm^3	kg/m^3	lb/ft^3	$lb/inch^3$	oz/gal
1	1000	62.43	0.03613	133.5265
0.001	**1**	0.06243	3.61E−05	0.133527
0.016018	16.01794	**1**	0.000579	2.138889
27.67783	2.77E+04	1728.011	**1**	3696
0.007489	7.48915	0.467532	0.000271	**1**

TABLE AI/1.4.0-2 Specific Gravity of Selected Materials

Material	Type	Specific Gravity	Remarks
Alcohol ethyl	Liquid	0.789	
Alcohol methyl	Liquid	0.792	
Ammonia	Gases	0.596	NH_3
Benzene	Liquid	0.897	
Butane	Gas	2.067	C_4H_{10}
Carbon dioxide	Gas	1.529	CO_2
Carbon monoxide	Gas	0.9671	CO
Ethylene	Gas	0.9749	C_2H_4
Ethylene glycol	Liquid	1.0658	50%
Hydrogen	Gas	0.06952	H_2
Nitric acid	Liquid	1.0554	10%
Sea water	Liquid	1.025	
Sodium hydroxide	Liquid	1.109	10%
Sulfur dioxide	Gas	2.2638	SO_2
Sulfuric acid	Liquid	1.066	

water at 15.6°C. The specific gravities of gases given here are based on the density of air at °C at 1 atm pressure as 1.

1.4.3 VISCOSITY UNIT CONVERSION FACTORS

Viscosity unit conversion factors have been enumerated in two tables: Table AI/1.4.0-3 (absolute viscosity) and Table AI/1.4.0-4 (kinetic viscosity).

Viscosities of a few important liquids have been presented in Table AI/1.4.0-5.

Viscosities of a few important gases have been presented in Table AI/1.4.0-6.

TABLE AI/1.4.0-3 Absolute Viscosity Conversion Factors

Centipoise	Pascal-s	lbm/ft-s	Poise
1	0.001	6.72E−04	0.01
1000	**1**	0.0672	1.00E+01
1.49E+03	14.8809524	**1**	14.87
100	1.00E−01	0.0672495	**1**

TABLE AI/1.4.0-4 Kinetic Viscosity Conversion Factors

Stoke	Centistoke	ft^2/s	cm^2/s
1	100	0.001076	1
0.01	**1**	0.00001076	0.01
929	1000	**1**	929
1	1437	0.001076	**1**

1.5.0 Length Conversion Factors

Length (distance) unit conversion factors have been enumerated in Table AI/1.5.0-1.

1.6.0 Flow Conversion Factors

Flow rate can be volumetric or mass flow rate. Unit conversions for both volumetric and mass flow rates have been indicated below.

1.6.1 VOLUMETRIC CONVERSION FACTORS

Volumetric flow rate unit conversion factors are given in Table AI/1.6.0-1.

1.6.2 MASS FLOW RATE CONVERSION FACTORS

Mass flow rate unit conversion factors are given in Table AI/1.6.0-2.

TABLE AI/1.4.0-5 Viscosity Values of Selected Liquids

Materials	Absolute Viscosity	Temperature (°C)	Liquid Type
Benzene	0.6	24	Newtonian
Butter fat	20	65	Newtonian
Chocolate	280	49	Thixotropic
Cod oil	32	38	Newtonian
Condensed milk	40—80	40—50	Newtonian
Cottage cheese	30,000	18	Thixotropic
Cream 50% fat	55	32	Newtonian
Ethyl alcohol	1.07	24	Newtonian
Ethylene	18	21	Newtonian
Fruit juice	55—75	18	Newtonian
Polyester	3000	30	Thixotropic
Resin solution	880 (7140)	24 (18)	Thixotropic
Sauce—Apple	500	80	Thixotropic
Sodium hydroxide 30% (40%*)	1.0 (*20)	18 18	Newtonian
Toothpaste	70,000—100,000	18	Thixotropic
Yoghurt	152	40	Thixotropic

TABLE AI/1.4.0-6 Viscosity Values of Selected Gases

Gaseous Material	Viscosity (CP) at 20°C	Viscosity (CP) at 100°C	Viscosity (CP) at 100°C
Ammonia	0.0099	1.30	1.68
Benzene	0.0075	0.0094	0.012
Carbon dioxide	0.0147	0.0185	0.0230
Carbon monoxide	0.0174	0.0210	0.0252
Chlorine	0.0132	0.0169	0.0210
Ethylene	0.0103	0.0128	0.0154
Methane	0.0110	0.0135	0.0163
Steam	0.0097	0.0124	0.0162
Sulfur dioxide	0.0126	0.0164	0.0209

TABLE AI/1.5.0-1 Length (Distance) Unit Conversion

Inch	Foot	Centimeter	Meter	Yard
1	0.083	2.54	0.0254	0.02777778
12	**1**	30.48	0.3048	0.333333
0. 3937	0.0328	**1**	0.01	0.0109361
39.37	3.28	100	**1**	1.09361
36	3	91.44	0.9144	**1**

TABLE AI/1.6.0-1 Volumetric Flow Rate Unit Conversion Factors

gal/h	Imp.gal/h	LPM	LPH	m^3/h	oz/min	y^3/h
1	0.83267	0.06309	0.001052	0.003785	2.133333	0.004951
1.200956	**1**	0.07576	0.001263	0.004546	2.562	0.005946
15.850372	13.1995776	**1**	0.016667	0.06	33.814	0.07847
951.02235	791.974657	60	**1**	0.001	0.563567	0.001308
2.64E+02	219.973603	16.666667	0.277778	**1**	563.567	1.30795
0.4687501	3.90E−01	0.0295735	0.000493	0.001774	**1**	0.00232
201.9794	168.180289	12.743724	0.212395	0.764555	431.0345	**1**

TABLE AI/1.6.0-2 Mass Flow Rate Unit Conversion Factors

g/min	g/s	kg/min	kg/h	mt.ton/h	lb/min	lb/h
1	0.166667	0.001	0.06	6.00E−05	0.002205	0.132277
60	**1**	0.06	3.6	0.0036	0.132277	7.93662
1000	16.66667	**1**	60	0.06	2.2046	132.276
16.66667	0.277778	0.166667	**1**	1.00E−03	0.03674	2.2044
1.67E+04	277.7778	16.66667	1000	**1**	36.7437	2204.622
453.5924	7.5599	0.4535924	27.21554	0.0272155	**1**	60
7.55987	0.1259979	0.0075598	0.453588	4.54E−04	0.016667	**1**

Appendix III may be referenced for unit conversions pertinent to **force, torque, power, time, and energy**.

2.0.0 FLOW PROPERTIES

In this part a few flow properties are discussed further. We start with flow regime and Reynolds number.

2.1.0 Flow Regime and Reynolds Number

From the discussions in Chapter I it has been noted that at low flow, i.e., at low velocities and high viscosities, the fluid particles move in an orderly manner in layer forms, as already discussed. The fluid flows in layers, meaning in well-ordered adjacent sliding layers. This is known as laminar flow. Before we move on it is better to recall Reynolds number as the unitless quantity. The Reynolds (Re) number is a quantity which by definition, as already explained, takes into account both velocity and viscosity, and is used to estimate the flow regime, i.e., if a fluid flow is laminar or turbulent. This is important, because increased mixing and shearing occur in turbulent flow. When the Re is between 0 and 2300 it is laminar. Reynolds number is critical at 2300, as at this point with reasonable accuracy the transition takes place. Therefore, Re values between 2300 and 4000 are the transition flow regime. Reynolds numbers above 4000 mean turbulence starts, so Re $>$ 4000 is turbulent flow. These are shown in Fig. AI/2.1.0-1.

2.2.0 Pressure Loss and Reynolds Number

Pressure loss is an important parameter in fluid flow measurement and it varies with the type of fluid, as well as the type of meter used. In a straight pipe with internal diameter D, fluid flows with average velocity v, the pressure loss H_v can be expressed in terms of length of pipe by the Darcy-Weisbach equation:

$$H_v = \lambda \cdot \frac{L}{D} \cdot \frac{v^2}{g} \qquad \text{(AI/2.2.0-1)}$$

where λ is the resistance coefficient g is acceleration due to gravity. The resistance coefficient is dependent on Reynolds number.

With laminar flow (Re $<$ 2300) the resistance coefficient is *independent* of pipe roughness and is given by

$$\lambda = \frac{64}{Re} \qquad \text{(AI/2.2.0-2)}$$

However, from the start of any turbulence, i.e., at transition as well as in turbulent flow, it is given by the Prandtl-Colebrook equation

$$1/\lambda^{1/2} = -2\log\left[2.51/\left(Re\lambda^{1/2}\right) + (K/D_h)/3.72\right] \qquad \text{(AI/2.2.0-3)}$$

Here K is pipe roughness, and D_h is hydraulic diameter, which for a full pipe is equal to D. Relative roughness D/K is normally available in tabular forms in piping handbooks.

3.0.0 SOLID FLOW PROPERTIES

In this section, the properties of solid flows discussed in Chapter VIII have been consolidated to arrive at the numerical expression for flowability.

3.1.0 Solid Flow Characteristic Features and Essential Properties

For flow of bulk solid material flow properties are quite important to address flow problems, i.e., flow obstructions, segregation, irregular flow, flooding, etc. When the discussions on material properties discussed in Section 1.2.0 of Chapter VIII are

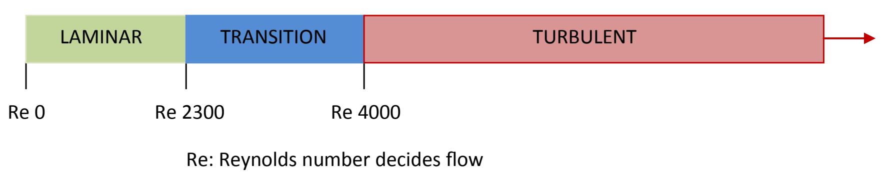

FIGURE AI/2.1.0-1 Flow regime and Reynolds number.

recalled one would find that the flow properties depend on several main parameters:

- Particle size distribution;
- Particle shape;
- Particle chemical composition;
- Particle moisture content;
- Particle temperature.

Often it is assumed that the behavior of a bulk solid is like that of fluids. This is not correct in many cases, so such assumptions often are misleading. The major important issues already discussed have been consolidated here as these are very important.

Stress: This is because of the fact that in Newtonian fluids the stresses in all directions should be of equal magnitude. However, the behavior of a bulk solid is quite different from that.

Adhesive forces: As indicated in Chapter VIII, the flowability of a bulk solid depends on the adhesive forces between individual particles. For fine-grained, dry bulk solids, adhesive forces due to van der Waals interactions play an important role.

Wall friction: Friction between the wall and solid surface of bulk materials.

Liquid bridge: For moist bulk solids, liquid bridges between particles usually are most important.

3.2.0 Flowability for Solid Flows

Flowability represents flow behavior. Good flowability means that bulk solid flows easily, i.e., it does not consolidate much and flows out of a container such as a "silo" or "hopper" by the force of gravity alone, without the aid of promoting devices such as vibrator. In contrast to this are products that are "poorly flowing" when they experience flow obstructions or consolidation during storage or transport. These are all qualitative statements.

These can be expressed in quantitative forms also. However, prior to that it is important to know what flow in bulk solids is. "Flowing" means that a bulk solid is deformed plastically due to the loads acting on it. The magnitude of the load necessary for flow is a measure of flowability. This can be demonstrated with the uniaxial compression test. There are a number of factors which influence flowability as already discussed in Sections 1.2.2 and 1.2.3 of Chapter VIII. So, major factors are listed here:

- Time consolidation (caking);
- Yield limit;
- Mohr stress circles.

Flowability can be characterized numerically by its unconfined yield strength (σ_c) in relation to consolidation stress (σ_1), and storage period, t. Usually the ratio ff_c of consolidation stress, σ_1, to unconfined yield strength, σ_c, is used to characterize flowability numerically as:

$$ff_c = \frac{\sigma_1}{\sigma_c} \qquad \text{(AI/3.2.0-1)}$$

Flowability characteristics based on numerical values have been illustrated in Fig. AI/3.2.0-1 to show flowability characteristics from *free flowing* to *not flowing*.

As indicated earlier, flowability-related properties are: angle of repose, bulk density, friction forces, and compressibility.

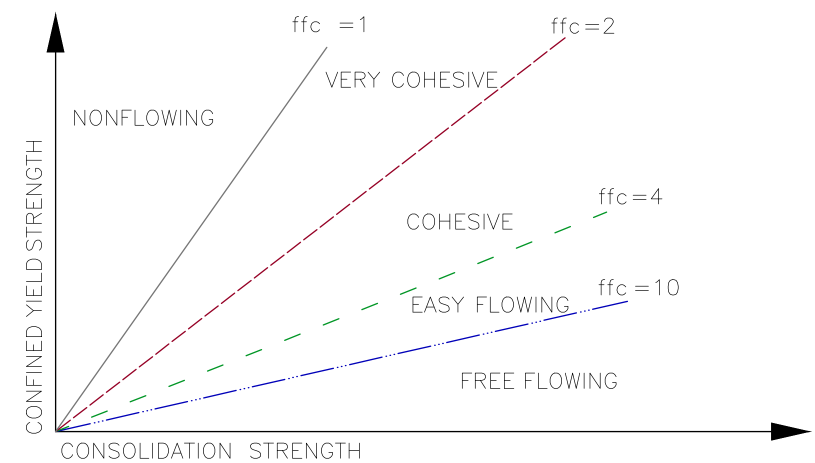

FIGURE AI/3.2.0-1 Flowability characteristics.

APPENDIX II

MATERIAL SELECTION GUIDE

In this section short discussions will be presented on how materials are selected for flow meters. This is discussed in three parts, i.e., background chemistry discussions, general material selections with pros and cons of materials normally encountered in flow metering, and specific discussions on a few flow meters, such as Coriolis mass flow meters for fluids, electromagnetic flow meters, and turbine meters to name a few. It is worth noting that standard materials charts are available with almost all meter manufacturers, as well as on the internet, so these are not repeated in this book. These charts may be consulted for any specific process material. From the chart one can get a number of materials available for particular process fluid. With these materials in mind one has to look into the material chart offered by the manufacturers (or the book) for the closest material available. If the closest material is not available for a product then it may not be selected and alternatives should be looked for. The discussions in this book are meant for the reader to develop a basic idea of why material selection is important and how to carry out the same to get better result from their selections.

1.0.0 BRIEF DISCUSSIONS ON CHEMISTRY

1.1.0 Background Chemistry for Material Selections for Flow Meters

Often it is a misconception in the mind of many designers that it is enough to select the materials for meter matching with the alloys selected for the piping system. This is not always true, because piping materials are selected on general corrosion considerations, whereas in the case of flow meters/flow elements localized corrosion or cyclic loading and abrasion considerations needs to be considered, e.g., the main steam pipes may be made up of alloy steel but flow nozzles are selected from 316 SS normally. Since flow meters and metering pumps (need to produce desired output performance and) may be subject to widely variable environments, naturally it is extremely difficult to find possible material combinations to meet process fluid compatibility. Halogen concentration, pH, chemical potential, and temperature are major factors in selecting suitable materials for the application. If these variables can be defined for a particular environment, comparisons of alloy limitations can be made and a compatible material of construction chosen [1].

1.1.1 CHEMICAL REACTION ISSUES FOR SOME METALS

In this section brief discussions are given on major causes of chemical reactions of metals (selected metals only).

1. **Halogens:** As we know, *halogen* refers to elements like chlorine, fluorine, bromine, and iodine with the Cl^- ion being the most commonly available ion. Stainless steel is suitable for many applications but is not really a good solution when Cl^- ions are present (except very low levels). Temperature and

moisture make things worse. Pitting and corrosion fatigue are common problems in such cases. Nickel alloy C22 could be used. In operation temperatures of about 540°C, nickel, Inconel 600, and Hastelloy B are extremely resistant alloys. Hastelloy C is suitable for service up to 480°C.

2. **pH:** The pH of a solution is an indication of its acidity or alkalinity and also influences the corrosion behavior. A solution with pH near 7 is neutral and naturally will be less aggressive. Strong acidity ($pH < 3$) and alkalinity ($pH > 11$) would be very corrosive. Nickel alloy C22, Tantalum, and also 316SS (to some extent) have good corrosion resistance in neutral and acidic environments. In alkaline applications, Nickel alloy C22 is recommended.
3. **Chemical potential:** The chemical potential or *redox* potential ($H_2 \rightarrow 2H^+ + 2e^-$ half reaction is considered as the basis for definition) is a measure of the oxidizing or reducing power of a process fluid. Chemical potential is often defined relative to this. Chemical potentials that are equal to or less than the reference are considered reducing, while chemical potential greater than the reference is considered oxidizing. A minimum amount of oxidizing power is required to enable the formation of protective surface oxide. Excess oxidizing or reducing will prevent stable oxide formation [1]. Inconel and Monel have good corrosion resistance and are often used in offshore and power applications with sea water.
4. **Charts:** Based on the above discussions a chart showing some selected materials against these chemical issues discussed in Subsections 1.1.1.1 through 3 has been depicted in Fig. AII/1.1.0-1.

1.2.0 Corrosion

Corrosion is an important phenomenon which can deteriorate the performance of flow meters as well as control valves or metering pumps. In this section brief discussions will be presented to give some idea of this.

1.2.1 DISCUSSIONS ON THE CORROSION PROCESS

Corrosion is a very complicated mechanism that occurs due to electrochemical reactions. Corrosion is the deterioration of a *metal* as a result of chemical reactions between it and the surrounding environment. The presence of apparently unnecessary factors like humidity, temperature, contaminants, or metal chlorides manipulates the corrosion level. Both "type of metal (material)" and the "environmental conditions (especially gases)" in contact with the metal, determine the form and rate of deterioration due to corrosion.

General corrosion occurs when the atoms on the same metal surface are oxidized and damage the entire surface. When reduction and oxidation take place on different kinds of metal in contact with one another, the process is called **galvanic** corrosion. This occurs mainly in electronic devices. Some metals acquire a natural passivity, or resistance to corrosion. This occurs when the metal reacts with, or corrodes in, the oxygen in air. The result is a thin oxide film that blocks the metal's tendency to undergo further reaction. All metals corrode but some corrode faster while some corrode slower such as; when pure iron, corrode quickly but SS is slower. Noble metals, such as silver, platinum, and gold, are much less reactive than others.

1.2.2 TYPES OF CORROSION PROCESS

Various metallic corrosions can be avoided by adding alloys to a pure metal. Others can be prevented by a careful combination of metals or management of the metal's environment. There are many types of metallic corrosions and these are enumerated below:

1. **General corrosion:** This is the most common form of corrosion, which is a uniform attack on the entire surface of a metal structure, caused by chemical or electrochemical reactions. It is a known and predictable result on account of the uniform attack that proceeds uniformly over the entire exposed surface area to cause metal to fail finally after becoming thinner.

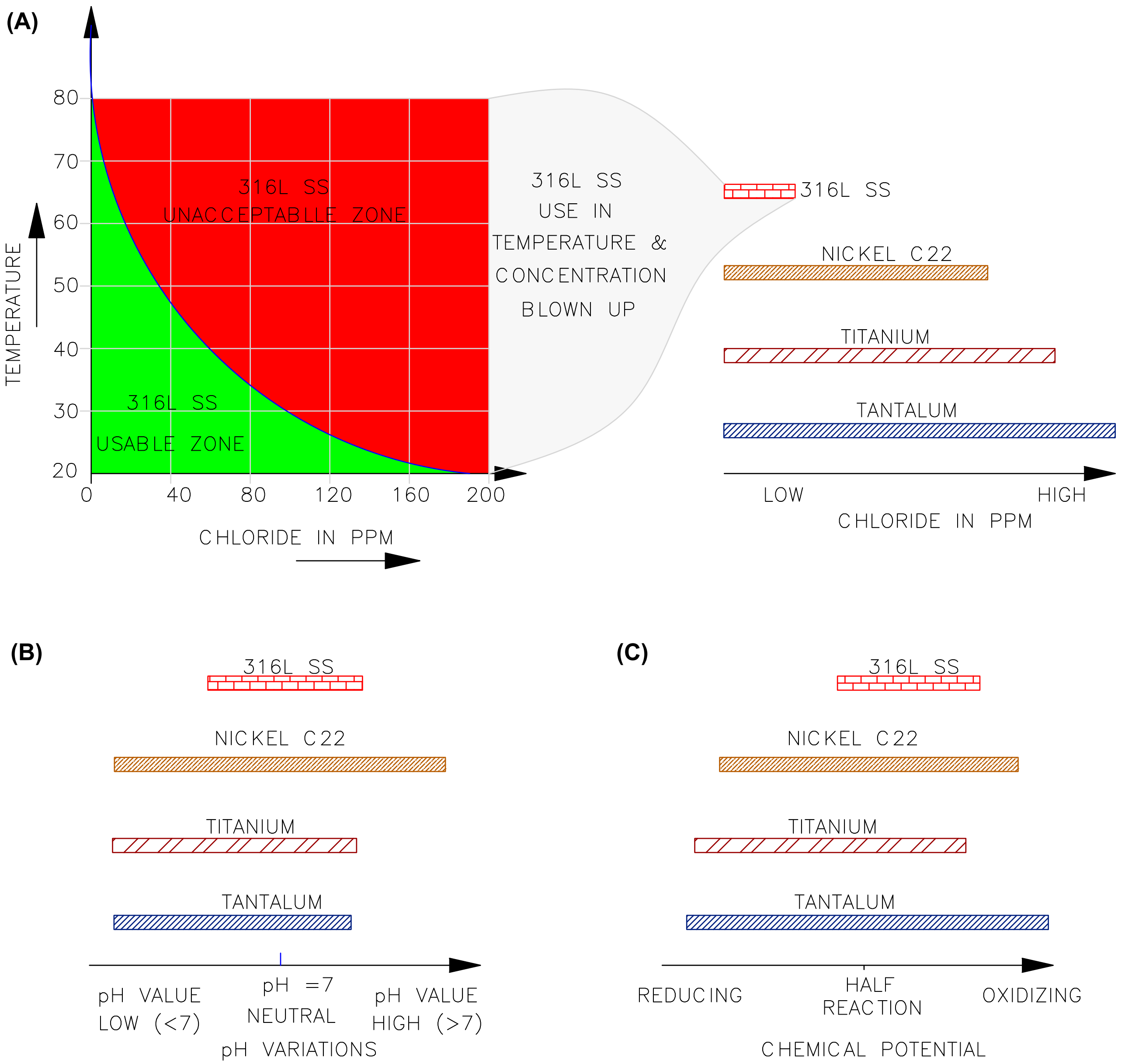

FIGURE AII/1.1.0-1 Chemical conditions and material behavior. (A) Material reaction with chloride ion concentration. (B) pH variations. (C) Chemical potential variations. *Developed based on Micro Motion® Corrosion Guide for Coriolis Flow and Density Meters, Density meters, and Viscosity Meters, GI-00415, Rev H, Micro motion; Emerson Process Management, January 2014; http://www2.emersonprocess.com/siteadmincenter/PM%20Micro%20Motion%20Documents/Corrosion-Guide-GI-00415.pdf. Courtesy: Emerson Process Management.*

2. **Localized corrosion:** Localized corrosion attacks a very *specific* location of a metal structure under a specific set of conditions. This is a very important consideration for flow meters. There are several types of localized corrosion such as pitting, crevice attack, and microbially influenced corrosion (MIC), to name a few:
   - *Pitting:* Pitting is a form of very localized corrosion that creates initially small holes in the surface of a metal. These small holes can propagate very quickly, leading to material perforation and failure in a very short period of time.
   - *Crevice corrosion:* These occur in stagnant locations. such as those found under gaskets. The microenvironment within the crevice can greatly differ from the general medium. This can progress very fast.
   - *Filiform corrosion:* Corrosion that occurs when water gets under a coating such as paint and creates weakness.
   - *Microbially influenced corrosion (MIC):* MIC is a form of crevice attack caused by certain types of bacteria forming dome-shaped colonies on the metal surface. The inside of the structure is sealed from the outside. The life cycle of the bacteria produces a corrosive environment within the colony which causes a crevice attack of the metal.

   There are a few other types of fatigues and corrosions such as the following:
   - *Corrosion fatigue:* Reduction of fatigue resistance;
   - *Stress corrosion cracking:* Presence of stress tensile stress with corrosion;
   - *Liquid metal cracking:* A special form of stress cracking;
   - *Hydrogen embrittlement:* Common in boiler tubes (i.e. molecular hydrogen coming out of metal surface);
   - *Intergranular corrosion:* Selective attack of a metallic component at the grain boundaries by fluid.
3. **Environmental cracking:** This attack occurs as a result of chemical conditions within the environment and the mechanical condition of the metal itself. This can cause cracking, fatigue, or embrittlement.
4. **Galvanic corrosion:** As explained earlier, galvanic corrosion results from the electrical coupling of two dissimilar metals in a corrosive medium resulting in the attack of the less resistant metal. The less noble material becomes anodic, while the more noble becomes cathodic. The anodic material actually protects the cathodic, leading to its own accelerated decay. The *farther* apart the materials are in the series, the greater is the likelihood of attack of the less noble material.
5. **Erosion corrosion:** Erosion corrosion is an acceleration in the rate of deterioration or attack on a metal because of relative movement between a corrosive medium and the metal surface. With *rapid* movements this can cause mechanical wear or abrasions.
6. **Dealloying:** Dealloying is the selective removal of one element of a solid alloy by a corrosion process. A common example is dezincification.

For an effective prevention system, it starts at the design stage with a proper understanding of the environmental conditions and metallurgical properties. It is essential to have good knowledge of possible chemical interactions.

2.0.0 FAMILIARIZATION WITH COMMONLY USED MATERIALS

This section basically give a brief account of the materials as a guide and general aid in selecting the appropriate materials to be used in flow applications. Because chemicals and their properties can vary greatly, this is to be used at your discretion.

2.1.0 Metals and Alloys

In this section commonly used metals for flow metering have been discussed.

2.1.1 STAINLESS STEEL

Discussions on some stainless steel types are discussed here.

1. **17-4 PH stainless steel:** This is a hardening stainless steel with high strength and hardness. It can withstand corrosive attack. There are three main types of PH stainless steel: low-carbon martensitic, semiaustenitic, and austenitic.
2. **301 stainless steel:** This exhibits corrosion resistance similar to 304SS listed below. It is a good choice as a metallic diaphragm material.
3. **303 stainless steel:** This stainless steel features physical properties that make it a good choice as a metallic diaphragm material with limited compatibility with a number of process fluids.
4. **304 stainless steel:** This is often used as a casing material, as it is less expensive than SS316, which can better withstand corrosion attack.
5. **316 stainless steel:** This is an alloy of iron, carbon, nickel, and chromium. It is a nonmagnetic stainless steel with ductility. It belongs to the group of austenitic stainless steels. This is essentially nonmagnetic and cannot be hardened by heat treatment. The nickel content contributes to the improved corrosion resistance, and it is also responsible for the retention of the austenitic structure. 316 stainless steel has excellent corrosion resistance to a wide range of chemicals. It is not susceptible to stress corrosion cracking. It is not affected by heat treatment. 316 stainless steel is the most widely used material in instruments deployed in process plants.
6. **430 (430F) stainless steel:** 430 stainless steel is a ferritic, straight chromium alloy. This alloy is nonhardenable but has excellent corrosion resistance at higher temperatures and possesses average mechanical properties. This grade is easily formable, making it excellent for large complex geometries. It finds its use in flow meters, e.g., turbine flow meters.

2.1.2 CAST IRON AND CARBON STEEL

1. **Cast iron:** This is an alloy of iron, carbon, and silicon. It can be easily cast. Cast iron has excellent dampening properties and is easily machined. The cost of cast iron is moderately favorable compared with stainless steel and it is often selected for industrial water treatment chemicals when acceptable [2].
2. **Carbon steel:** Both carbon steels and stainless steels contain iron, which oxidizes when exposed to the environment, creating rust. It is an alloy of iron and carbon, with the carbon content up to a maximum of 1.5%−2.0%. Carbon steel does not typically have enough chromium to form this chromium oxide layer, allowing oxygen to bond with the iron which results in iron oxide, or rust. The mechanical properties in some cases are very close to SS however, it depends on many different types and grades of each. They are less ductile when compared with SS because of nickel. Its temperature-withstand capability is nearly up to 300°C.

2.1.3 HASTELLOY TYPES

Hastelloys are material in the nickel-molybdenum family of alloys.

1. **Hastelloy B:** This has excellent resistance to hydrochloric acid at all concentrations and temperatures. Hastelloy B exhibits high thermal stability and excellent resistance to sulfuric, acetic, formic, and phosphoric acids, and other nonoxidizing media.
2. **Hastelloy C:** Hastelloy C also contains chromium. It exhibits outstanding resistance to a wide variety of chemical process environments, including strong oxidizers such as sodium hypochlorite and ferric chloride. Hastelloy C is also resistant to nitric, hydrochloric, and sulfuric acids at moderate temperatures.

2.1.4 NICKEL, MONEL, AND INCONEL TYPES

1. **Nickel:** Nickel shows good mechanical properties coupled with aqueous corrosion resistance. These are good for use in caustic soda and synthetic fiber production, and for food handling, etc. There are two kinds of alloys: nickel 200 and 201. Nickel 201 has low carbon and can prevent intergranular embrittlement at above 600°F (315°C).
2. **Monel:** This is an Ni–Cu alloy with high strength and excellent resistance to a range of media including seawater, dilute hydrofluoric and sulfuric acids, and alkalis. Monel 400 finds its use in marine and offshore engineering. Monel K500 is another Monel alloy.
3. **Inconel:** This is an Ni–Cr–Fe alloy with resistance to stress-corrosion cracking and caustic corrosion, and with high-temperature strength and oxidation-resistance. There are many alloys of Inconel and they find their use in instrumentation in corrosion applications. There are several alloys of Inconel available, including Inconel C276, 622, 600, 725. At ambient temperatures Alloy-400 (67Ni–33Cu) has good resistance to most of the nonoxidizing acids. It also resists nonoxidizing salts. The nickel in the alloy improves its resistance toward alkalis. It is more susceptible to hydrogen permeation. In Alloy C-276 (54Ni–16Mo–16Cr), chromium and molybdenum are added to nickel to improve the alloy's resistance to oxidizing conditions. This alloy also retains a considerable degree of resistance to nonoxidizing conditions.

2.1.5 TANTALUM AND TITANIUM

1. **Tantalum:** Tantalum surface alloys offer a new route to corrosion resistance in severe corrosion environments. Tantalum, having wide acceptance in the chemical industry, is a very useful material in corrosive applications involving hydrochloric acid and acidic ferric chloride solutions. Tantalum has good strength even at elevated temperatures. Its high strength allows thin sections to be used. It is very expensive.
2. **Titanium:** Whenever titanium is exposed to the atmosphere or to any environment containing oxygen, it immediately acquires a thin tenacious film of oxide (TiO_2, Ti_2O_3, and TiO). Titanium's corrosion resistance comes from a protective oxide film which is strongly adherent and stable. A stable, substantially inert oxide film provides the material with outstanding resistance to corrosion in a wide range of aggressive media including and particularly to highly corrosive environments with oxidizing and chloride-containing process streams. However, strong reducing media may cause heavy corrosion.

2.2.0 Nonmetallic Commonly Used Materials

There are a number of nonmetallic materials used for flow-metering purposes. These are described here.

2.2.1 NONMETALLIC NONELASTOMERIC MATERIALS

Following are commonly used nonmetallic and nonelastomeric materials in flow metering.

1. **Acrylic:** This is a kind of plastic offering resistance to many chemicals and which is clear like glass (also referred to as acrylic glass) and is in some cases preferred to other plastics.
2. **Ceramic:** High alumina (96%–99.5% Al_2O_3) content ceramics find their applications in flow meters and bearings. Ceramic has the advantages of having a high level of hardness while being very corrosion-resistant to a wide range of chemicals even at elevated temperatures. This is, however unsuitable for hydrofluoric, hydrofluorosilicic, and hydrochloric acids.
3. **Polyethylene and polypropylene:** Polyethylene shows very good chemical resistance to strong acids, bases, and is also resistant to some oxidants and reducing agents. Polypropylene offers very high chemical resistance to all the above cases and organic solvents. However, it is slightly lower in physical properties compared to PVC and it is not very effective in not strong oxidizing acids, chlorinated hydrocarbons, or aromatics.

4. **PVC:** PVC is the most common form of thermoplastic material, which is characterized by high physical properties and resistance to corrosion and chemical attack by acids, alkalis, salt solutions, and many other chemicals. It cannot withstand high temperatures, with a maximum limit of between 50 and 60°C. It is not successful in handling ketones, some chlorinated hydrocarbons, and aromatics [2].
5. **PVDF:** This is a strong and abrasion-resistant fluorocarbon material [2]. It resists distortion and retains most of its strength to 135°C. PVDF is excellent with most acids, bases, and organic solvents.

2.2.2 NONMETALLIC ELASTOMERIC MATERIALS

These are some materials which are used as seals, O-rings, and linings. There are many such materials and some of them are registered trademarks of some chemical/metallurgical companies. The majority of these materials are listed below:

1. **Aflas:** This is a type of polymer and is resistant to petroleum products and phosphate-esters. Temperature range −30 to 210°C. It is typically used for O-rings in various pump models.
2. **Buna N:** This is known as nitrile rubber—a general purpose oil-resistant polymer. Service temperature is in the range of ∼− 30 to 80°C. It is resistant to most solvents, oils, water, and hydraulic fluid.
3. **EPDM:** EPDM has good abrasion and tear resistance and offers excellent chemical resistance to a variety of acids and alkalis. It is not recommended for applications involving petroleum oils, strong acids, or strong alkalis. Service temperature is in the range of ∼− 30 to 120°C.
4. **Kalrez:** This is a highly expensive material but at times is the only choice available when others are not suitable because it shows chemical resistance to most of the chemicals normally used. It can withstand temperatures up to 170°C.
5. **PEEK:** This is a high-performance engineered thermoplastic that can be used as a diaphragm material. It can withstand temperatures up to nearly 300°C.
6. **PTFE:** This is very common and offers outstanding resistance to chemical attack by most chemicals and solvents. Service temperature range ∼− 30 to 150°C.
7. **Viton:** This is compatible with a broad range of chemicals (not suitable with methanol) [2]. The Viton O-ring is common. Service temperature range ∼− 30 to 150°C.

3.0.0 MATERIALS AND USES IN SELECTED FLOW METERS

In this section short discussions will be presented on various materials used in different flow-measuring instruments. This is a generalized discussion and there can be several variations also. As this is based on applicable fluids there will be variation in materials, so material specifications given here mainly pertain to *wetted parts* only. In main text some of these have been covered, these are given here in a consolidated manner. Only a few commonly used materials from reputed manufactures have been presented here. Readers should use their discretions in consultation with the manufacturer(s).

3.1.0 Coriolis Mass Flow Meter for Fluid Meter Tube

1. Stainless steel 1.4571, 1.4435, Tefzel-lined 316L;
2. Hastelloy C;
3. Nickel alloy C22;
4. Tantalum;
5. Titanium.

3.2.0 Differential Pressure Transmitter

The following materials are used in process transmitters (DPTs) for flow elements.

1. **Diaphragm:** commonly used diaphragm materials are listed here:
   - 316L SST (UNS S31603);
   - Alloy C-276 (UNS N10276);
   - Alloy 400 (UNS N04400);
   - Tantalum (UNS R05440);
   - Gold-Plated Alloy 400;
   - Gold-Plated 316L SST.

2. **Drain vent valves:** Materials for drain and vent valves include the following:
   - 316L SST (UNS S31603);
   - Alloy C-276 (UNS N10276);
   - Alloy 400/K-500 (Drain vent seat: Alloy 400; Drain vent stem: Alloy K-500).
3. **Process flange/adapter:** Process flange and adapter materials include the following:
   - Plated carbon steel;
   - CF-8M (Cast 316 SST) (UNS J92900);
   - *Cast C-276:* CW-12MW-1 (UNS N10276);
   - *Cast Alloy 400:* M-30C (UNS N04400).
4. **O-ring:** O-ring materials include the following:
   - Glass-filled PTFE;
   - Graphite-filled PTFE;
   - Graphite (available as a special option).

3.3.0 Electromagnetic Flow Meter

The following materials are commonly used in electromagnetic flow meters.

1. **Electrodes:** Of the various electrode materials the following are commonly used:
   - Stainless steel 1.4571, stainless steel 1.4539;
   - Hastelloy B, Hastelloy C;
   - Ni—C276;
   - Platinum—20%iridium;
   - Tantalum;
   - Titanium.
2. **Liner:** There is a wide choice of materials for liner including the following:
   - Ceramic carbide;
   - ETFE;
   - Hard rubber, Linatex rubber, soft rubber;
   - Neoprene;
   - Peek, PFA, PTFE;
   - Polyurethane;
   - PVDF;
   - Torlon.

3.4.0 Thermal Mass Flow Meter

Normally the following materials are used for thermal mass flow meters:

1. **Meter tube:** Meter tubes are made up of:
   - Stainless steel 1.4571;
   - Hastelloy.
2. **Sensor:** Sensors are made up of:
   - Stainless steel 1.4571;
   - Hastelloy;
   - Ceramic.

3.5.0 Turbine Flow Meter

The following are typical materials for turbine meters. In this connection Section 2.4.1 of Chapter V may be referenced. Some typical materials are listed here:

1. **Housing material:** 316 stainless steel;
2. **Rotor material:** 430F stainless steel;
3. **Ballbearing material:** 440C stainless steel or equivalent, ceramic;
4. **Journal-bearing material:** Ceramic, tungsten carbide, graphite.

3.6.0 Vortex/Swirl Meters

1. **Meter tube:** Meter tube materials include the following:
   - A105/WCB forge/cast CS;
   - HastelloyC;
   - Stainless steel 1.4571/ASTMECF8, SS316, and CF3M.
2. **Sensor:** Sensing materials include the following:
   - Stainless steel 1.4571;
   - HastelloyC.
3. **Shedder:** Shedder materials include the following:
   - Stainless steel 1.4571, Duplex steel;
   - HastelloyC.
4. **Gasket:** Gasket materials include the following:
   - Graphite;
   - PTFE;
   - Kalrez;
   - Viton (A);
   - SUS316 SS with Teflon coating.

In the following section, different fluids and materials to be used have been illustrated with the help of a table.

4.0.0 MATERIAL COMPATIBILITY

In Table AII/4.0.0-1 the material compatibility of flowing medium and meter materials have been illustrated.

TABLE AII/4.0.0-1 Material Compatibility

Fluid Types	Fluid Type	Approx Concentration	Approx. Temperature	Conductive	SS304 Metal	SS321 Metal	316L Metal	Hastelloy B Metal	Hastelloy C Metal	Titanium Metal	Tantalum Metal	Platinum Metal	Hard Rubber – Non Metal	Soft Rubber – Non Metal	PFA – Non Metal	PTFE – Non Metal	EPDM – Non Metal	Buna N – Non Metal	Viton – Non Metal	PVDF – Non Metal	PVC – Non Metal	Glass – Non Metal	Ceramic – Non Metal
Acetic acid	L	80	40	Y	R	R	R	R	R	R	R	R	R	R	R	R	R	NR	NR	NR	NR		R
Acetone	G		60	N	R	R	R	R	R	R	R	R				R	R	NR		R	NR		
Acetylene	G	100	20	N	R	R	R	R	R	R	R	R	R	R		R	R	R				R	R
Ammonia	G	100	50	N	R	R	R	R	R	R	NR	R	NR	NR		R	R	R	NR	NR	NR	R	R
Beer	L		10	Y	R	R	R	R	R	R	R	R			R	R	R		R		R	R	R
Benzene	L	100	50	N	R	R	R	R	R	R	R	R	NR	NR	R	R					NR	R	R
Brine	L		20	Y	NR	NR	NR	NR	R		R	R								NR			
Butane	G	100	50		R	R	R	R	R	R	R	R	R	R	R	R	NR	R	R	NR	NR	R	R
Butylene	G	100	20	N	R	R	R	R	R	R	R	R			R	R	R	R	R		R	R	R
Calcium chloride sol	L	100	20	Y	R		R	R	R		R	R	R	R	R	R	R	R	R	R	R	R	R
Carbon dioxide	G	100	50	N	R	R	R		R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Chlorine dry	G	100	20	N	R	R	R	NR	R		R		R	NR	R	R	NR		R	R	R	R	R
Chlorine wet	G	100	20	N	NR	R	NR	NR	R	NR	R		NR	NR	R	R	NR		R	R	R	R	R
Copper chloride sol	L	50	20	Y	NR	NR	R	NR	R	R	R	R	R	R	R	R		R		R	R	R	R
Copper sulfate sol	L	50	80	Y	R	R	R	NR	R	R	R	R	R	NR	R	R	R	R	R	R	NR	R	R
Diesel fuel	L	100	50	N	R	R	R	R	R	R	R	R	NR	NR	R	R	R	R		R	R	R	R
Ethanol	L	96	50	N	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	NR		R	
Ethyl alcohol	L	100	80	N	R	R	R	R	R	R	R	R	R	R		R		R			NR	R	R
Fatty acid	L	100	50	N	R	R	R	R	R	R	R	R	NR	NR	R	R			R		R	R	R
Ferric chloride sol	L	10	20	Y	NR	NR	NR	NR	NR	R	R	R	R	R	NR	R	R	R	R	R	R	R	R
Gasoline	L	100	20	N	R	R	R	R	R	R	R	R	R	NR	NR	R	NR		R	R	NR	R	R
Glycol	L	100	50	N			R	R	R	R	R	R			R	R			R	R			R

Continued

TABLE AII/4.0.0-1 Material Compatibility—cont'd

Fluid Types	Fluid Type	Approx Concentration	Approx. Temperature	Conductive	SS304 Metal	SS321 Metal	316L Metal	Hastelloy B Metal	Hastelloy C Metal	Titanium Metal	Tantalum Metal	Platinum Metal	Hard Rubber – Non Metal	Soft Rubber – Non Metal	PFA – Non Metal	PTFE – Non Metal	EPDM – Non Metal	Buna N – Non Metal	Viton – Non Metal	PVDF – Non Metal	PVC – Non Metal	Glass – Non Metal	Ceramic – Non Metal
Hydrazine Sol	L	25	20	Y	R	R	NR					R	NR	NR	R	R	R	NR		R	R	NR	NR
Hydrochloric acid	L	37	20	Y	NR	NR	NR	R	R	R	R	R	R	NR	R	R	NR	NR	R	R	R	R	R
H_2 peroxide sol	L	40	20	Y	R	R	R		R	NR		NR	NR	NR	R	R	R		R	R	NR	R	
Kerosene	L	100	20	N	R		R								R	R		R	R			R	
Methanol	L	100	50	N	R	R	R	R	R	R	R	R	R	R	R	R	R	R	NR	R	NR	R	R
Natural gas	G	100	40	N	R	R	R	R	R	R	R	R	NR	NR	R	R	NR	R		R	R	R	R
Nitric acid	L	20	40	Y	R	R	R	NR	R	R	R	R	NR	NR	R	R	NR	NR	NR	R	R	R	R
Olive oil	L		50	N	R	R	R	R	R	R	R	R	R	NR	R	R		R	R	R	R	R	R
Oxygen	G	100	50	N	R	R	R	R	R		R	R			R	R	R		R	NR	NR	R	R
Petroleum	L	100	20	N	R	R	R	R	R		R	R	NR	NR	R	R	NR	R	R	R	R	R	R
Phenol	L	90	50	N	NR	R	R	R	R	R	R	R	NR	NR	R	R	NR	NR	NR	R	NR	R	R
Phosphoric acid	L	30	50	Y	NR		R	R	R	NR	R	R	NR	NR	R	R	R	NR	R	R	NR	R	R
Sea water	L		50	Y	NR		NR	NR	R	R	R	R	R	R	R	R	R	R	R	R	NR	R	R
Sodium bicarbonate	L	20	50	Y			R	R	R		R	R	R		R	R		R	R	R		R	R
Sulfuric acid	L	10	50	Y	NR	R	NR	R	R	NR	R	R	R	R	R	R	NR		R	R	R	R	R
Toluene	L	100	50	N	R	R	R	R	R				NR	NR	R	R	NR	NR	R	R	NR	R	R
Urea	L	30	50	Y		R			R		R	R	R	R	R	R	R	R	R	R	NR	R	R
Wort	L		5	Y	R	R	R	R	R	R	R	R			R	R	R		R		R	R	R
Yeast	L		20		R	R	R	R	R	R	R	R	R	R	R	R	R	R	R		R	R	R

The following details may be noted prior to going through the table. Fluid type: *L*, liquid; *G*, gaseous; Temperatures are expressed in degree Celsius. Symbols: *R*, recommended; *NR*, not recommended; *X or blanks*, not known or not applicable.
For preparation of the table some data are taken from ABB Flow handbook. F. Frenzel, H. Grothey, C. Habersetzer, M. Hiatt, W. Hogrefe, M. Kirchner, G. Lütkepohl, W. Marchewka, U. Mecke, M. Ohm, F. Otto, K.-H. Rackebrandt, D. Sievert, A. Thöne, H.-J. Wegener, F. Buhl, C. Koch, Deppe, E. Horlebein, A. Schüssler, U. Pohl, B. Jung, H. Lawrence, F. Lohrengel, G. Rasche, S. Pagano, A. Kaiser, T. Mutongo, Industrial Flow Measurement Basics and Practice, ABB Automation Products GmbH. http://nfogm.no/wp-content/uploads/2015/04/Industrial-Flow-Measurement_Basics-and-Practice.pdf. Courtesy: ABB Limited.

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APPENDIX III

MECHANICAL AND PIPING DATA (INCLUDING FLANGE DATA)

While in Appendix II short discussions were given on process parameters, compatibility, etc. Mechanical and piping data are also equally important, especially for in-line flow meters. It is also important for flow elements as well as for insertion type flow-metering devices. This appendix is dedicated to dealing with essential mechanical and piping data and standards in connection with flow metering. The discussion begins with unit conversions for force, torque, power, and energy not covered in Appendix I where unit conversions of other pertinent parameters have been dealt with.

1.0.0 UNIT CONVERSIONS FOR FORCE, TORQUE, POWER, AND ENERGY

1.1.0 Unit Conversion for Force

We first consider force based on which many flow meters function, e.g., a target flow meter. Unit conversion of forces has been illustrated in Table AIII/1.1.0-1. In this table gm force, kilo Newtons, and ounce forces have not been considered as these can be easily calculated using the following sums:

- 1 kgf = 1000 gf {multiplying factor 1000};
- 1 N = 0.001 kN {multiplying factor 0.001};
- 1 lbf = 16 ozf {multiplying factor 16}.

1.2.0 Unit Conversion for Torque

We now consider the torque unit conversion. Many instruments are based on this e.g., target flow. Even for tightening a bolt in a flange this is important. Unit conversion of torque has been illustrated in Table AIII/1.2.0-1. Basically, this is similar to force, only length is multiplied by it. The following conversions may be noted:

gf·cm = 1E−05 kgf·m;
1 kNf·m = 0.001 N·m;
1 lbf·ft = 192 oz·inch (16 × 12).

TABLE AIII/1.1.0-1 Unit Conversion Factors for Force

Dyne	Kilo Force	Newton	Pound Force	Poundal
1	1.02E−06	1.00E−05	2.25E−06	7.23E−05
9.80E+05	**1**	9.80665	2.204623	70.93164
1.00E+05	1.00E+05	**1**	0.224808	7.233013
4.44E+05	0.4535923	4.44824	**1**	32.17404
1.38E+04	0.0140981	0.138255	0.031080958	**1**

TABLE AIII/1.2.0-1 Unit Conversion Factor for Torque

Dyne·cm	Kgf·m	lbf·ft	N·m
1	1.00E−08	7.40E−08	1.00E−07
1.00E+08	**1**	7.233013	9.80665
1.35E+07	1.38E−01	**1**	1.355818
1.00E+07	0.1019716	0.737562	**1**

1.3.0 Unit Conversion for Power

Let us now consider power unit conversion. Unit conversion factors for power have been illustrated in Table AIII/1.3.0-1. Power is defined as work done per second, so in this table all units are in terms of seconds. However, at times power is expressed in terms of work done per minute (or per hour). This can be done by converting the time scale:

Time: 1 h = 60 min = 3600 s (as 1 min = 60 s).

1.4.0 Unit Conversion for Energy

Let us now consider energy unit conversion. Unit conversion factors for energy have been illustrated in Table AIII/1.4.0-1 (***1 dyne-cm = 1 erg***).

TABLE AIII/1.3.0-1 Unit Conversion Factor for Power

BTU/s	Cal/s	HP	Kilowatt	lbft/s
1	2.52E+02	1.41E+00	1.05E+00	7.77E+02
3.97E−03	**1**	0.00561	0.004183	3.085279
7.07E−01	1.78E+02	**1**	0.7456999	550
9.48E−01	239.06287	1.341022	**1**	737.5621
1.29E−03	0.3241198	0.001818	0.001355818	**1**

BTU, British thermal unit (thermal energy), calorie thermal energy; *HP*, horse power, normally electrical/mechanical energy.

TABLE AIII/1.4.0-1 Unit Conversion Factor for Energy

BTU	Calorie	Electron Volt	erg	HP hours	Kilowatt hour
1	2.52E+02	6.58E+21	1.05E+10	3.93E−04	2.93E−04
3.97E−03	**1**	2.61E+19	4.19E+07	1.56E−06	1.63E−06
1.52E−22	3.83E−20	**1**	1.60E−12	5.97E−26	4.45E−26
9.52E−11	2.39E−08	6.25E+11	**1**	3.72E−14	2.78E−14
2.54E+03	6.41E+05	1.68E+25	2.69E+13	**1**	7.46E−01
3.41E+03	6.13E+05	2.25E+25	3.60E+13	1.34E+00	**1**

2.0.0 PIPING DATA

In this section brief discussions on piping data are covered. These are necessary for flow meter designs, i.e. flow element, in-line flow meter, fixing insertion length for insertion type meters. The discussion starts with pipe specifications.

2.1.0 Pipe and Tube Specification

There are some differences in specifying pipes and tubes. It is not the intent of this book to detail pipe specifications according to different standards; here only basic guidelines are provided. The discussions start with pipe specifications.

2.1.1 PIPE SPECIFICATIONS

Normally pipes are specified in terms of nominal bore which is an imaginary diameter (usually—not always) between the outer and inner diameters. As soon as nominal bore (NB) is specified its outer diameter (OD) is fixed (i.e. fixed relation between NB and OD). Based on the schedule (— to be specified with NB for complete specification) the thickness and hence the inner diameter of the pipe are decided. Typical NB, inlet, and outlet diameters of a pipe have been shown in Fig. AIII/2.1.0-1.

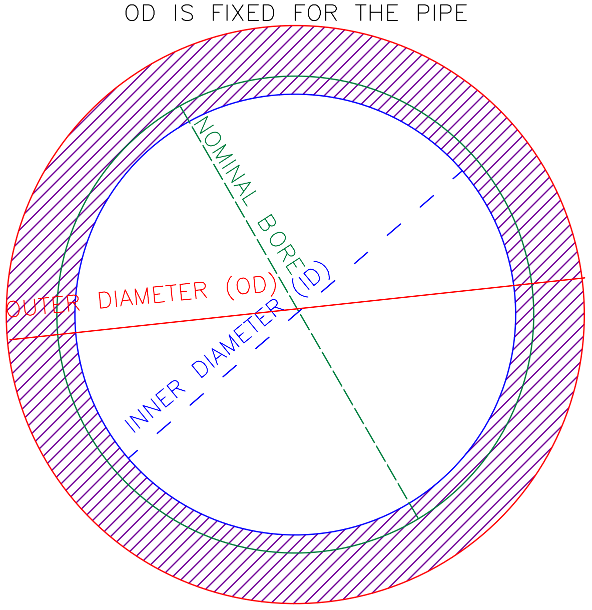

FIGURE AIII/2.1.0-1 Pipe specification.

These are explained as follows:

1. **Pipe diameter:** Two commonly used size standards are:
   - *In Imperial units:* US standards: Nominal pipe size (NPS)/nominal bore (NB)
     (US standards: ANSI/API/ASME)
   - *In metric units:* EU-DIN standard: Pipe diameter: Nominal diameter (DN)
   - Once DN/NB is specified, OD is fixed.
2. **Pipe schedule:** This sets the pipe wall thickness. A greater wall thickness of the pipe will result in increased mechanical strength of the pipe to handle higher design pressures. The following pipe schedules are available (in order of increasing wall thickness): 5S, 10S, 10, 20, 30, 40S, STD, 40, XS (Extra Strong), 60, 80, 100, 120, 140, XXS (Double Extra Strong), and 160.
3. **Pipe internal diameter (ID):** For process and instrument engineers, the most important information is the pipe internal diameter (ID), as this is primarily used in specifying straight length, as well as for in line sizing calculations. As indicated before, for a given NB, the pipe OD remains constant. So, with pipe schedule changes, the internal diameter of the pipe changes.

TABLE AIII/2.1.0-1 Diameter Nominal (DN) and Nominal Pipe Size (NPS)

Diameter Normal	Nominal Pipe Size	Diameter Normal	Nominal Pipe Size
6	1/8	150	6
8	1/4	200	8
10	3/8	250	10
12	1/2	300	12
20	3/4	600	24
25	1	800	32
40	1½	1050	42
50	2	1500	60
65	2½	1800	72
80	3	2000	80
100	4	2200	88

TABLE AIII/2.1.0-2 Dimensional Details of Pipes

		Sch10		Sch40		SchXS*		Sch160		SchXXS	
DN	OD	Thk	ID	Thk	ID	Thk	ID	Thk	ID	Thk	ID
15	21.34	2.11	17.12	2.77	15.80	3.73	13.88	4.78	11.78	7.47	6.40
20	26.67	2.11	22.45	2.87	20.93	3.91	18.85	5.56	15.55	7.82	11.03
25	33.40	2.77	27.86	3.38	26.64	4.45	24.30	6.35	20.70	9.09	15.22
40	48.30	2.80	42.70	3.70	40.90	5.10	38.10	7.10	34.10	10.2	27.90
50	60.30	2.80	54.70	3.90	52.50	5.50	49.30	8.70	42.90	11.1	38.10
80	88.90	3.00	82.90	5.50	77.90	7.60	73.70	11.1	66.70	15.2	58.50
100	114.3	3.00	108.30	6.00	102.3	8.60	97.10	13.4	87.50	17.1	80.10
150	168.3	3.40	161.50	7.10	154.1	11.0	146.3	18.3	131.7	22.0	124.3
200	219.1	3.80	211.50	8.20	202.7	12.7	193.7	23.0	173.1	22.2	174.7
250	273.0	4.20	264.60	9.30	254.4	15.1	242.8	28.6	215.8	25.4	222.3
300	323.9	4.60	314.70	10.3	303.3	17.5	228.9	33.3	257.3	25.4	273.1
600	610.0	6.35	597.30	9.53	590.94	12.70	584.60	59.40	491.20		

Table AIII/2.1.0-1 provides the relation between DN (mm) and nominal pipe size (NPS in inches) in line with ASME.

Pipe dimensions for various pipe sizes at different schedules have been enumerated in Table AIII/2.1.0-2.

2.1.2 TUBE SPECIFICATION

In contrast to pipes, tubes are specified in terms of outer diameter and thickness. The main specifications in selecting tubes are listed here:

- Surface finish;
- Material;
- Hardness;
- Wall thickness.

Typical stainless tube dimensional details and pressure ratings have been enumerated in Table AIII/2.1.0-3. These data are taken from reputed manufacturers.

At elevated temperatures there will be a derating, which will be governed by a factor as indicated in Table AIII/2.1.0-4.

TABLE AIII/2.1.0-3 Stainless Steel Tube Dimensional Details and Pressure Rating (Typical)

Outer Diameter	Thickness	Tube Inside Diameter	Working Pressure
6	1	4	420
6	1.5	3	600
10	1	8	294
10	1.5	7	398
10	2	6	498
12	1	10	245
12	1.5	9	368
12	2	8	426
15	1	13	196
15	1.5	12	294
15	2	11	392
25	2.5	20	294
25	3	19	353

Tube Dimensions are in mm and pressure rating is in bar.

TABLE AIII/2.1.0-4 Pressure Derating Factor at Elevated Temperature

Temperature (°C)	304/304L Stainless Steel	316/316L Stainless Steel
93	1.00	1.00
204	0.93	0.96
315	0.82	0.85
426	0.76	0.79
537	0.69	0.76

3.0.0 FLANGE DATA

There are several types of flanges and there a few international standards, such as ANSI/API/BS/DIN/JIS etc. to specify them. We first investigate flange types. For further details any standard book on flange may be referenced.

3.1.0 Flange Types

Flange types can be classified as per their connection types as well as flange face types. We investigate flange classifications according to their connection types.

3.1.1 FLANGE CONNECTION TYPES

According to the connection type and style the most commonly used flange types include the following:

1. **Welding neck:** Welding neck flanges have a long tapered hub, which goes gradually over to the wall thickness from a pipe or fitting. This long tapered hub provides an important reinforcement for use in high pressure, and subzero and/or elevated temperatures. These flanges are bored to match the inside diameter of the mating pipe or fitting so there will be no restriction of product flow. This prevents turbulence at the joint and reduces erosion. They also provide excellent stress distribution through the tapered hub and easy radiography for flaw detection is possible.
2. **Slip on:** The calculated strength from a slip on flange is much lower as compared to the welding neck type. However, from an installation point of view it is easier. The connection with the pipe is done with two fillet welds, as well as at the outside and the inside of the flange. A disadvantage of the flange is, in principle, a pipe must always firstly be welded and then adjust the fitting.
3. **Socket weld:** Socket weld flanges can be used for small-size high-pressure piping, it has strength equal to the slip on type with greater fatigue strength. The connection with the pipe is done with a fillet weld, at the outside of the flange. However, before welding, a space must be created between the flange or fitting and the pipe in line with the standard (e.g., ASME B31.1 1998). In this type there will be an expansion gap inside which must be a right gap—the concerned standard may be referenced.
4. **Lap joint:** This type is very similar to a slip on flange. It does not have a raised face and can accommodate the stub end. It has pressure-handling capability near that for a slip on type flange. Lap joint flanges have certain special advantages:
   - Freedom to swivel around the pipe;
   - No contact with fluid in the pipe, hence low-cost materials can be used.

   The stub end type is used with a lap joint flange, as a backing flange. Stub ends are available in almost all pipe diameters. This cheap flange connection normally is applied in low-pressure and noncritical applications.
5. **Threaded:** Threaded flanges are attached to the pipe without welding. Sometimes a seal weld is also used in addition to the threaded connection. Although these are available in various sizes they are mainly applied for smaller pipe sizes at lower pressure ratings.
6. **Blind flange:** Blind flanges are manufactured without a bore as these are used to blank off the ends of piping, valves, and pressure vessel openings. These flanges are suitable for higher-pressure and higher-temperature applications.

3.1.2 FLANGE FACE TYPES

Different types of flange faces are used at the contact surfaces to seat the sealing gasket

material. ASME B16.5 and B16.47 define various types of flange facings:

1. **Raised face (RF):** Raised face type shown in Fig. AIII/3.0.0-1B, is the most common type used in process plant applications, and is easy to identify due to its raised face to accommodate the gasket surface which is raised above the bolting circle face. This face type allows the use of a wide combination of gasket designs. In the RF flange more pressure is concentrated on a smaller gasket area to increase the pressure containment capability of the joint. The height (1.6–6.4 mm) of the RF is determined by the pressure rating.
2. **Flat face (FF):** The flat face flange as shown in Fig. AIII/3.0.0-1A has a gasket surface in the *same* plane as the bolting circle face. Applications using flat face flanges are frequently those in which the mating flange or flanged fitting is made from a casting. It should never be connected to the RF flange on the other end.
3. **Ring-type joint (RTJ):** The ring type joint flanges are typically used for high pressure (≥Class 600 rating) and/or high-temperature services above 427°C. Ring-type joint flange types have been depicted in Fig. AIII/3.0.0-1C. They have grooves cut into their faces with steel ring gaskets. The flanges seal when tightened bolts compress the gasket between the flanges into the grooves, deforming (or coining) the gasket to make intimate contact inside the grooves, creating a metal-to-metal seal. An RTJ flange may have a raised face with a ring groove machined into it. This raised face does not serve as any part of the sealing means. Ring type joint gaskets are metallic sealing rings, suitable for high-pressure and high-temperature applications.
4. **Tongue and groove type:** The tongue and groove faces of these flanges must be matched. One flange face has a raised ring (tongue) machined onto the flange face, while the mating flange has a matching depression (groove) machined into its face.
5. **Male-and-female (M&F):** In this type, the flanges also must be matched. One flange face has an area that extends beyond the normal flange face (male). The other flange or mating flange has a matching depression (female) machined into its face.

Various flange face types with dimensional details for FF, RF, and RTJ flanges have been depicted in Fig. AIII/3.0.0-1.

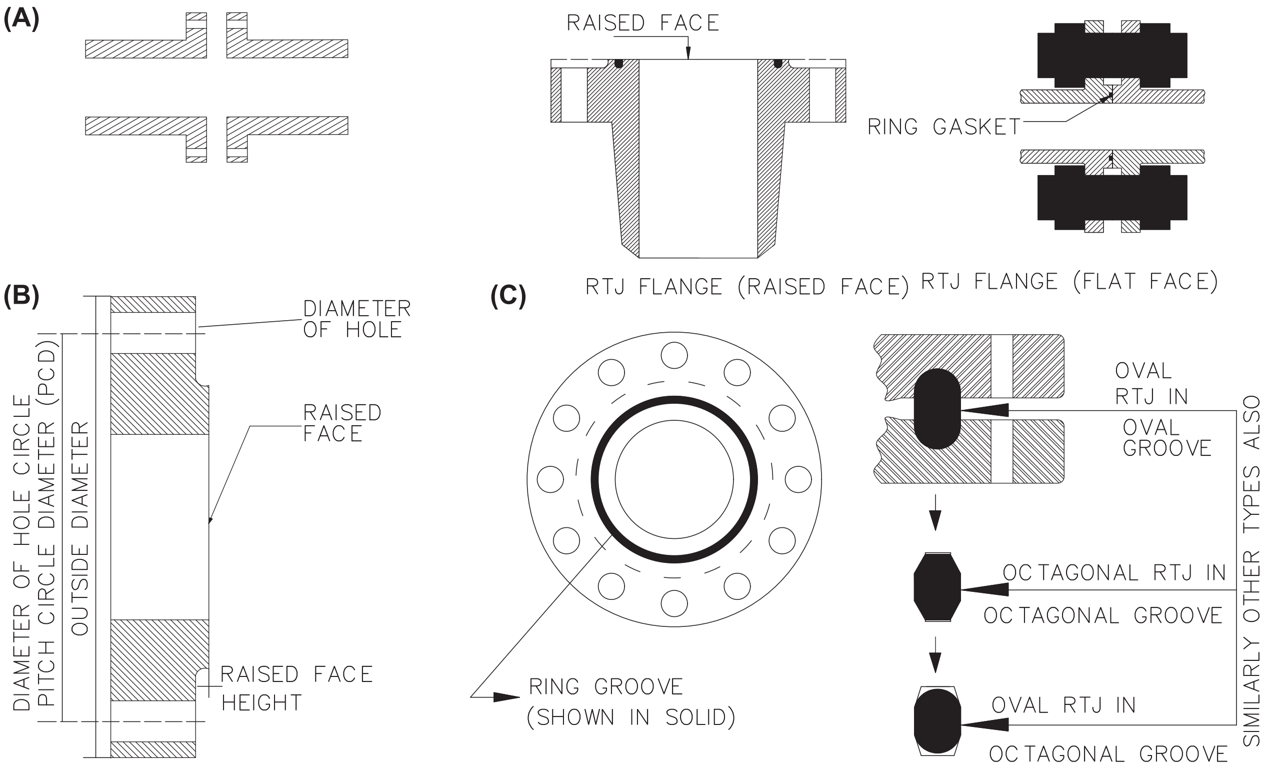

FIGURE AIII/3.0.0-1 Flange types. (A) Flat face flange. (B) Raised face flange. (C) Ring type joint flange.

3.2.0 Flange Standards and Dimensions

Flanges are available in various forms with each following particular standards, of these the following are quite commonly used internationally.

3.2.1 MAJOR STANDARDS

The following are major standards are used for flanges internationally:

1. **British Standard:** BS10:1962. Withdrawn: 30th April 2009; Current status: BS EN 1092-1:2007+A1:2013;
2. **EU Standard:** European standard (EN): DIN EN 1092-1:2002-06 and 2007;
3. **German Standard:** German National Standards Institute (DIN):DIN2527;
4. **Japanese Standard:** Japanese Industrial Standards: B2220:2004;
5. **US Standard:** American Society of Mechanical Engineers (ASME): ANSI B16.5:2009.

3.2.2 RAISED FACE HEIGHT

Table AIII/3.2.0-1 shows the typical height for raised faces (refer to Fig. AIII/3.0.0-1).

3.3.0 Flange Dimensional Details

Standard dimensional details of various flanges are easily available from the standards. We now look at comparisons of these for a few cases (Table AIII/3.3.0-1).

TABLE AIII/3.2.0-1 Raised Face Height

Standard	Flange Specification	Raised Face Height	
		In mm	In inch
ASME ANSI B16.5:2009	≤300 lb	1.6 (2)	0.06
ASME ANSI B16.5:2009	400, ≥600	6.4 (7)	0.25
DIN EN 1092-1:2007	≤DN 32	2	0.08
DIN EN 1092-1:2007	>DN 32 to ≤DN 250	3	0.12
DIN EN 1092-1:2007	>DN 250 ≤ DN 500	4	0.16
DIN EN 1092-1:2007	>DN 500	5	0.19
JIS 2220: 2004	≤DN 20	1.5	0.06
JIS 2220: 2004	>DN 20 ≤ DN 50	2	0.08
JIS 2220: 2004	> DN50	3	0.12

TABLE AIII/3.3.0-1 Flange Standards and Dimensions

Pipe	STD	Ratings	OD	PCD	Bolt	RF Dia.	Thick	Remarks
25	ASME	150	108	79	4 × 15.7	50.8	14.2	NPS1″
25	ASME	300	124	89	4 × 19.1	50.8	17.5	NPS1″
25	DIN	10, 16, 25*	115	85	4 × 14	68	16*	*18 for 25
25	JIS	10, 16, 20	125	90	4 × 19	67	14–16	

Continued

TABLE AIII/3.3.0-1 Flange Standards and Dimensions—cont'd

Pipe	STD	Ratings	OD	PCD	Bolt	RF Dia.	Thick	Remarks
50	ASME	150	152	121	4 × 19.1	91.9	19.1	NPS2″
50	ASME	300	165	127	8 × 19.1	91.9	22.4	NPS2″
50	DIN	10, 16, 25*	165	125	4 × 18	102	18	*20 for 25
50	JIS	10, 16*, 20*	155	120	4 × 19*	96	14–18	*8 × 19
80	ASME	150	190.5	152.4	4 × 19.1	127	23.9	NPS3″
80	ASME	300	209.5	168.1	4 × 22.4	127	28.4	NPS3″
80	ASME	600	209.5	168.1	8 × 22.4	127	31.8	NPS3″
80	DIN	10, 16, 25*	200	160	8 × 18	138	20*	*24 for 25
80	JIS	10	185	150	8 × 19	126	18	
80	JIS	16, 20*	200	160	8 × 23	132	20*	*22 for 20
100	ASME	150	228.6	190.5	8 × 19.1	139.7	23.9	NPS4″
100	ASME	300	254	200.2	8 × 22.4	157.2	31.8	NPS4″
100	ASME	600	273	215.9	8 × 25.4	157.2	38.1	NPS4″
100	DIN	10, 16	220	180	8 × 18	158	20	
100	DIN	25	235	190	8 × 22	162	24	
100	JIS	10	210	175	8 × 19	151	18	
100	JIS	16, 20*	225	185	8 × 23	160	22*	*24 for 20
200	ASME	150	342.9	298.5	8 × 22.4	269.7	28.4	8″
200	ASME	300	381	330.2	12 × 25.4	269.7	31.8	8″
200	ASME	600	419.1	349.3	12 × 32	269.7	55.6	8″
200	DIN	10, 16*	340	295	8* × 22	268	24	*12 for 16
200	DIN	25	360	310	12 × 26	278	30	
200	JIS	10	330	290	12 × 23	262	22	
200	JIS	16, 20*	350	305	12 × 25	275	26*	*30 for 20
250	ASME	150	406.4	362	12 × 25.4	323.8	30.2	10″
250	ASME	300	444.5	387.4	16 × 28.4	323.8	47.8	10″
250	ASME	600	508	431.8	16 × 35	323.8	63.5	10″
300	DIN	10	445	400	12 × 22	370	26	
300	DIN	16	460	410	12 × 26	378	28	
300	DIN	25	485	430	16 × 30	395	34	
300	JIS	10	445	400	16 × 25	368	24	
300	JIS	16,20*	480	430	16 × 27	395	30*	*36 for 20

Unless otherwise stated dimensions shown here are in mm (in reality ANSI flanges are in inches). Pipe, pipe nominal size (DN mm, for equivalence for NPS refer to Table AIII/2.1.0-1); For ASME 25, 50, 80, 100, 200, and 250 represent 1″,2″, 3″, 4″, 8″, and 10″, respectively. *OD*, outside diameter; *PCD*, pitch circle diameter; *STD*, standard.

4.0.0 GASKET SYSTEM

Gaskets are available in various forms. There can be nonmetallic filler, such as PTFE, ceramic, or metallic winding materials, such as different grades of SS, CS, titanium, etc. They can be color coded. There are different type of gaskets, such as spiral wound gasket, metallic serrated gasket, and metal jacketed gasket. The number of bolts on the flange and their sizes are guided by the standard for the flange. Bolting method and types has direct bearing on gasket compression. The bolting should be done cyclically (clockwise) with the recommended method of bolting as listed below:

- Torque to the bolts at 30% of the final loading using the appropriate bolt pattern;
- 60% of final load;
- 100% of final load;
- 100% of final torque using a clockwise pattern.

Based on the applied torque there will be *compression* of the gasket. Since there is some recommended applied toque there will be some recommended compression of the gasket as well, e.g., for optimum performance spiral wound gaskets have required compression for a gasket of thickness 1.6 mm to 1.3/1.4 mm or a gasket of 6.4 mm could be compressed to 4.6 mm. Gasket suppliers provide such lists for particular gasket types. Torque values limit minimum and maximum gasket seating stresses based upon pressure class and operating conditions (e.g., maximum pressure ratings for given pressure class). Extreme operating conditions, such as high temperatures, may *reduce* the bolt yield strength. Caution should be used in these applications. As stated earlier, there will be some recommended torque value for each of the bolt types based on its yield strength. The following are the basic assumptions considered to arrive at the recommended torques.

- Bolts are new, standard finish, uncoated, and not lubricated (other than the normal protective oil film);
- The load will be 90% of the bolt yield strength;
- The coefficient of friction is fixed and a standard value;
- The final tightening sequence is achieved smoothly and slowly.

Thus from this it is clear that based on bolt size and grade there will be a recommended torque. The torque and tension are related by:

$$M = \frac{P \cdot D}{K} \qquad \text{(AIII/4.0.0-1)}$$

where

Symbol	In Imperial System	In Metric System
D =	Bolt diameter in inch	Bolt diameter in mm
K =	Constant K = 60	Constant K = 5000
M =	Torque in lb·ft (pound feet)	Torque in N·m (Newton meter)
P =	Bolt tension (lb)	Bolt tension (Newton)

With this, the discussions on gaskets are concluded with the note that based on the application the gasket type to be chosen and applied torque on the bolt should be within the applicable limit to get better performance.

APPENDIX IV

CUSTODY TRANSFER (INCLUDING PROVER)

1.0.0 CUSTODY TRANSFER GENERAL DISCUSSIONS

Custody transfer applications are mainly connected with the oil and gas industries. It is needless to explain the requirements of flow metering in the oil and gas industries in which Custody transfer (CT) is a special flow measurement. In this section a general discussion on custody transfer has been presented. The discussion starts with a definition and explanation of the custody transfer system.

1.1.0 Explanation of Custody Transfer

Basically, flow measurements in oil and gas are important not only for taxation/custody transfer but also for allocation, reservoir management, well testing, environmental reporting, etc. Fluid flow measurement in custody transfer is defined as a metering point (location) where the fluid is being measured for sale (or other purposes discussed above) from one party to another. This means that it basically refers to a transaction involving transportation of fluid from one operator to another. The term “fiscal metering” is often interchangeably used with custody transfer to refer to metering at a point of a commercial transaction when a change in ownership takes place between two parties. The accuracy of measurement is of great importance to both parties, i.e., the seller and buyer. In a custody-transfer flow measurement, there can be one or two custody-transfer flow meters, i.e., one set measures the volume or mass of fluid before the transfer is made, and another set of flow meters measures the flow after the transfer. Custody transfer is unique among flow meter applications because of two major reasons:

- *Money changes hands;*
- *Requirement for very high accuracy.*

The requirement for high accuracy will be clear from a small example, e.g., 100 barrels/day, if it costs 10 billion USD then with 0.25% *uncertainty* the loss would be 20 million USD per day. Therefore, accuracy is extremely important for both parties, i.e., the party delivering the product as well as to the party that is the recipient of the product. This is because uncertainty could be in either direction (positive or negative) to cause a loss. For custody transfer, as any errors or uncertainty in measurement (for custody transfer) can be very expensive, custody transfer and fiscal metering in most countries are highly regulated, with the involvement of government taxation and contractual agreements between custody transfer parties. Proving must meet the following requirements:

- Traceable to a standard recognized by the International Bureau of Legal Metrology (BIML);
- Validated at operating conditions.

1.2.0 Some Standards and Associations for Custody Transfer

In general custody transfer (CT) involves the following:

1. Industry standards;
2. National metrology standards;
3. Contractual agreements between custody transfer parties;
4. Government regulation and taxation.

Custody transfers are also influenced by a number of industry standards and associations, i.e., American Gas Association (AGA), American Petroleum Institute (API), US National Institute for Standards and Technology (NIST), PhysikalischTechnische Bundesanstalt (PTB) in Germany, China Metrology Certificate (CMC), and gosudarstvennyy standart (GOST) in Russia [3]. Therefore, in custody transfer measurement, guidelines from these bodies are followed. AGA reports and API standards are very important and mostly used standards for measurement in custody transfer. In order to keep the uncertainty of measurement within limits as per the standards, not only is a highly accurate flow meter needed but also a system as detailed below.

1.3.0 Measuring System for Custody Transfer

In order to lower the uncertainty value and to get stable reliable measurements, a complete system, as shown in Fig. AIV/1.0.0-1, comprising the following will be necessary:

1. Multiple meter runs with multiple meters in parallel. Each is referred to as a stream;
2. Flow conditioning;

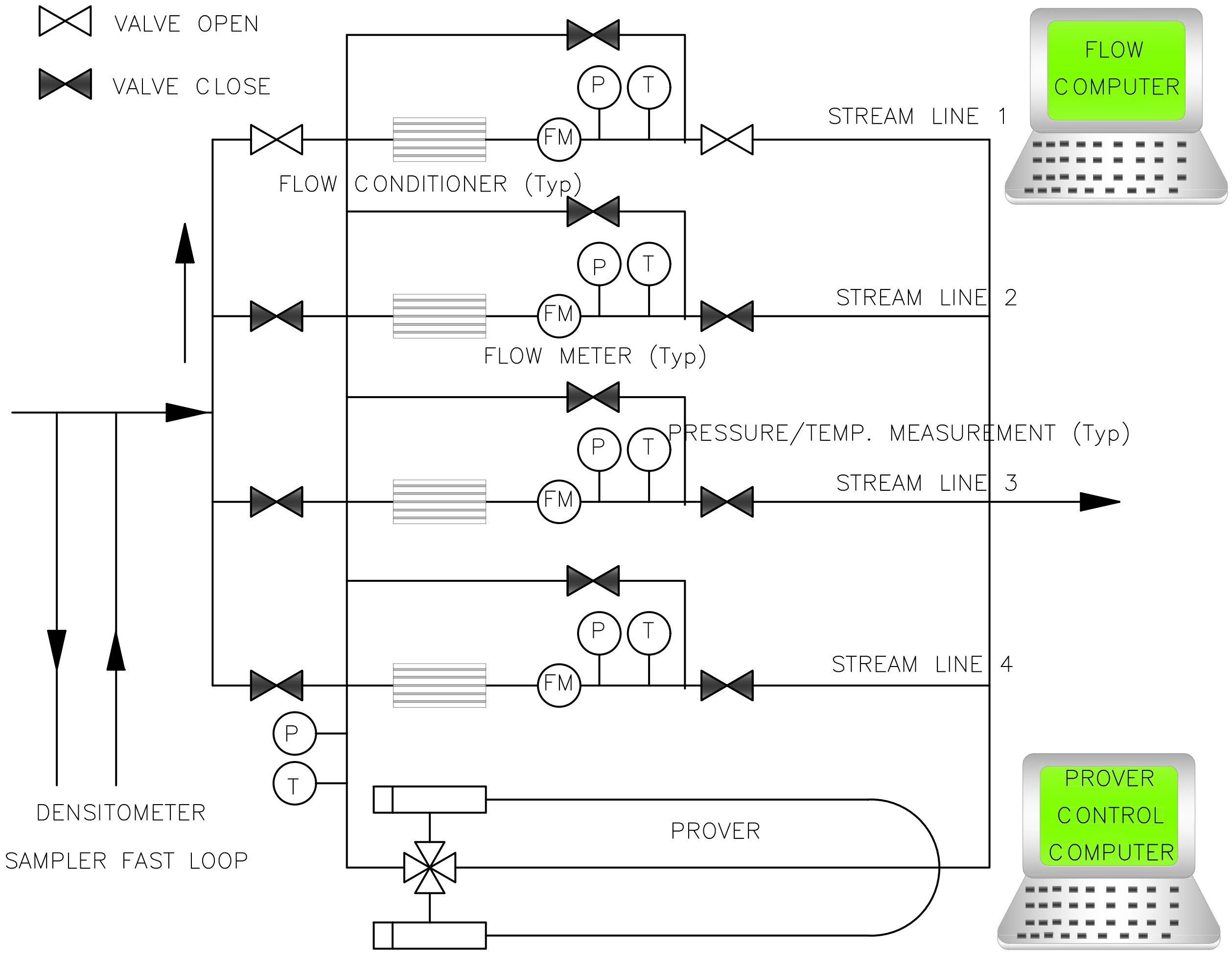

FIGURE AIV/1.0.0-1 Custody transfer measurement scheme.

TABLE AIV/1.0.0-1 Pros and Cons of Meter Types in Custody Transfer

Meter Type	Advantages	Disadvantages
DP type (orifice)	Low cost, easy installation, and comprehensive standard	High-pressure loss, edge erosion, longer upstream straight length
PD meter	Accurate, repeatable, fast response, direct measurement, insensitive installation effect	Bulky and complicated, mechanical damage, and expensive
Turbine meter	Moderate cost, easy installation, good repeatability	Mechanical damage, bearing wear, installation effect, contaminant effect
US flow meter	Nonintrusive and noninvasive, no moving parts, bidirectional, high diagnostic	High cost, installation effect, deposit on sensor
Coriolis meter	Noninvasive, independent of process parameter, high accuracy and turndown	High cost, high-pressure loss, zero stability, limited size vibration effect

3. Pressure measurement in each stream as well as the main stream;
4. Temperature measurement in each stream as well as the main stream;
5. Stream flow computers;
6. Meter prover/master meter;
7. Prover automation;
8. Density measurement [1];
9. Sampling system [1];
10. Flow computation;
11. Quality measurement
    - For gas energy content, online gas chromatography; gas composition
    - For liquids, sampling systems and water monitoring (BS&W).

1.4.0 Recommended Meter Types for Custody Transfer Measurements

The following flow meters have been accepted for custody transfer. In parenthesis the reference of acceptance of the meter for the measurement has been indicated.

1. DP type—orifice plate (1930 AGA1 report);
2. PD meter (API MPMS 5.2);
3. Turbine flow meter (1981: AGA 2 reprint 1982) (API MPMS 5.2);
4. Ultrasonic (AGA9: 1998) (API MPMS 5.11);
5. Coriolis mass flow meter (AGA11: 2003) (API MPMS 5.6).

We now look into the pros and cons of various meter types. Table AIV/1.0.0-1 shows the advantages and disadvantages of various meters used for custody transfer.

1.5.0 Role of AGA and API in Custody Transfer Metering

Two international organizations, American Gas Association (AGA) and American Petroleum Institute (API), studied custody transfer measurements and have come out with procedures for measurement. The AGA is more focused on industrial and natural gas, while the API focuses more on petroleum liquids. The AGA and API studied custody transfer measurement and published a series of reports specifying how this measurement is to be done with different types of flow meters [2]. As mentioned earlier, while the AGA's reports are mainly related to gas flow measurements, the API has issued its own reports on the use of flow meters involving custody transfer of liquids.

1. **AGA:** The first AGA report AGA-1 on custody transfer measurement was in 1930, a

report on the use of DP flow meters with orifice plates for custody transfer of gas. Currently AGA Report No. 3 Orifice Metering of Natural gas and Other hydrocarbon related fluids. In 1981, the AGA issued a report on custody transfer measurement—a report on the use of turbine flow meters for custody transfer applications. A current AGA report is a new version of AGA-7 entitled *Measurement of Natural Gas by Turbine Meters in 2006*. In 1998 the AGA issued AGA-9, a report detailing the use of ultrasonic flow meters for custody transfer applications. The AGA published AGA-11 in 2003, a report on the use of Coriolis flow meters for custody-transfer applications.
2. **API:** This deals more with liquids flow metering. Various API reports include API MPMS 5.2 (positive-displacement meters), API MPMS 5.3 (turbine meters), API MPMS 5.6 (Coriolis flow meters), and API MPMS 5.11 (ultrasonic flow meters). There are other API reports to cover vortex, magnetic, thermal dispersion, and variable area flow meters also.

Now some details on meter types, meter provers, etc. will be look into.

1.6.0 Meter Selection for Custody Transfer Metering

The following are the major characteristics to be considered while selecting a meter for custody transfer:

1. System characteristics;
2. Product characteristics;
3. Flow and viscosity range;
4. Accuracy (inherent accuracy as per API);
5. **Errors considerations (as applicable):**
   - Random error
   - Spurious error
   - Fixed and variable systematic error
   - Repeatability and linearity.

In this connection it is worth noting some guidance provided by the API standard.

According to the API, the following should be the major considerations for meter selection:

- The advantages of metering;
- Design of meter installations;
- *Meter performance:* For custody-transfer applications, meters with the highest inherent accuracy should be used and should be proven on site;
- *Meter proving:* Dependent on operating conditions.

1.7.0 Custody Transfer Measurements and Legal Issues

Custody transfer is fiscal measurement used to determine the quantity and associated financial value of a petroleum product transaction (delivery). The custody transfer is normally guided by two types, i.e., legal and contract.

1. **Legal:** Legal is defined by Weights and Measures (W&M) in the country or jurisdiction in which the *sale* is conducted. Naturally the W&M codes and regulations of the concerned country would control the wholesale and retail trade requirements for fair trade. Even though there may be wide variations in the requirements pertinent to the regulations and accuracy amongst various countries, there is one common characteristic—traceability.
2. **Contract:** A contract is basically a written agreement between buyers and sellers. This encompasses various requirements for the measurements as well as the accuracies (may be by referring to any international standard). These are large-volume sales between companies. In these the products are transported by marine, pipeline, or rail. Even with a very small error, there could be a large financial impact, therefore the custody transfer measurement must be at the highest level of accuracy possible and follow international standards. Such detailing are normally specified in the contract.

2.0.0 DISCUSSIONS ON METER TYPES USED IN CUSTODY TRANSFER

As we have seen above, there are five main meter types (basically four types and PD meter as an additional type for petroleum products) are approved for custody transfer measurement. In DP type flow metering, the orifice plate has been approved. To the best of my knowledge, V cone flow elements are also used in Canada for custody transfer measurement. All these flow-metering types have already been discussed in the main body of this book. Here a brief outline of these meters will be covered from custody transfer measurement points of view. The flow meters discussed here are arranged according to their principle of operations (also in the order they appear in the main body of the book).

2.1.0 Differential Pressure Type Flow Metering

The third AGA report on orifice metering for custody transfer, called AGA-3, was published in 1955 and reissued in 1992 and is currently in use as the standard (AGA3.1). Differential pressure (DP) flow meters are used for custody transfer (of natural gas) and can be used to measure the flow of liquid, gas, and steam.

1. **Principles:** DP type measurement with an orifice as the flow element is the commonest of flow-metering devices deployed for custody transfer. The DP flow meter consists of a differential pressure transmitter and a primary element (orifice plate). When discussions in Chapter II are recalled it can be seen that a machined plate with central hole is placed between two pipe pieces to create a constriction in the flow stream, while the DP transmitter measures the pressure differential between upstream and downstream of the constriction created by the flow element. Some suppliers also use DPT with an integral orifice plate, as already discussed in Chapter II.
2. **Approval:** Standards and criteria for the use of DP flow meters for custody transfer applications are specified by the American Gas Association (AGA) and the American Petroleum Institute (API).
3. **Features:** As this meter type is the most studied and best understood, this is an advantage in using DP type metering. Uncertainty offered by the metering system is moderate but it has a lower turndown ratio. Pressure loss and straight length requirements are some of the limitations of this measurement system. One important development in the use of DP flow meters for custody transfer applications has been the development of single- and dual-chamber orifice fittings [4].

2.2.0 Positive Displacement (PD) Type Flow Metering

Positive displacement (PD) flow meters offer high accuracy, and hence are widely used for custody transfer of commercial and industrial water, as well as for custody transfer of oil and gas applications (mainly petroleum products).

1. **Principles:** PD meters measure flow by momentarily isolating segments of *known* volume and counting them, i.e., known segments of fluid pass through the measurement chamber and these are counted. There are two factors which affect the accuracy of a PD meter—measuring *chamber* volume displacement and *slippage* through the capillary seals (clearances).
2. **Approval:** PD flow meters have been approved by a number of regulatory bodies (API). Measurement of low flow and flow of fluid with high viscosity are major advantageous points for PD meters. The speed of flow doesn't matter when using a PD meter.
3. **Features:** Performance of the meters are affected by two major factors, i.e., volume displacement and slippages. Let us look into these issues separately:
   - *Volume displacement: Temperature* and *coating* are two major issues which influence both displaced volume as well as measurement accuracy of the meter already

discussed in Chapter IV. With a change of temperature due to expansion or contraction of the materials, the volume of the measurement chamber will vary and hence the volume of the fluid is displaced. Most PD meter designs are not highly sensitive to temperature and can operate within the allowable measurement accuracy over a fairly wide temperature range [5]. Wax of crude oils can coat the inside of the measurement chamber and reduce volumetric displacement. This directly affects the meter factor and hence measurement accuracy.
- *Slippage:* PD meters have two parts, one moving and the other stationary, with minute clearances between them. Here a capillary seal is formed. As already discussed in Chapter IV, if there is any slippage, i.e., a small part goes to this seal part it gets unaccounted for and is known as slippage. At higher viscosity the slippage will be lower. For this reason it is seen that for a given accuracy or linearity, with an increase in viscosity the turndown ratio increases as detailed out in chapter IV.
- *Sizes:* Normally PD meters are common for smaller line sizes. On account of its bulky design meter >250 mm is not common.

4. **Advantages:** The meter offers a number of advantage points such as the following:
   - Superior accuracy and measurement stability;
   - Low-pressure drop;
   - Low operating cost;
   - Long service life with ease of maintenance;
   - Tolerance to entrained solids.

   On account of possible high accuracy these meters find applications as master meters also.

2.3.0 Turbine Type Flow Metering

Turbine flow meters are extensively used in custody transfer applications. Short discussions on the same are presented below.

2.3.1 PRINCIPLES OF OPERATIONS AND FEATURES OF TURBINE FLOW METERS

There are many types of turbine meters, but many of those used for gas flow are called axial meters.

Principle of operation: Turbine meters determine the flow rate by measuring the velocity of a bladed rotor suspended in the flow stream. The volumetric flow rate is the product of the average stream velocity and the flow area at the rotor. Turbine flow meters can be used for liquid and gas flow measurement. In 1981, the AGA:7 issued its report, “Measurement of Fuel Gas by Turbine Meters.”

Features: Various features of turbine flow meters have been enumerated in Chapter V. Major features concerning custody transfer could be summarized as follows:

- The turbine flow meters enjoy an edge over others for measuring clean, steady, high-speed flow of *low*-viscosity *fluids*;
- It is very cost-effective, especially in larger meter sizes when compared with USFM and Coriolis;
- On account of moving parts, there will be wear and tear in the meter to cause lowering of performance;
- Durable materials of construction are necessary to prevent wear and tear and assure better meter performance.

2.3.2 MEASUREMENT ACCURACY

The accuracy of a turbine meter is based on two assumptions: Constant *area* and precision stream *velocity* measurement.

1. **Constant area:** The flow area remains constant: Here meter factor k can change due to:
   - Erosion/corrosion/deposits;
   - Boundary layer thickness—Viscosity, hence Reynolds number is an influencing factor;
   - Cavitations;
   - Obstructions.

2. **Stream velocity:** The rotor velocity accurately represents the stream velocity: This assumption is changed on account of the following:
   - Fluid density;
   - Bearing friction;
   - Blade angle of the rotor;
   - Rotor stability;
   - Velocity profile change (calls for flow conditioning).

2.4.0 Ultrasonic Type Flow Metering

In 1998, the ultrasonic flow meter was included as a meter type in custody transfer (**AGA 9**). Over the past 10 years, ultrasonic flow meters, along with Coriolis flow meters, have become the flow meters of choice for custody transfer in the oil and gas industry.

2.4.1 PRINCIPLES OF OPERATIONS

Ultrasonic meters provide the volumetric flow rate by measuring the velocity of the flowing stream like turbine meters. Volume throughput is calculated by multiplying the velocity by the flow area. The flow area can be accurately determined by measuring the average internal pipe diameter in the measurement area. The *transit* time difference is proportional to fluid velocity, as discussed at length in Chapter V. The principle of measurement is simple but determining the *true* average velocity is difficult, especially to obtain custody transfer measurement accuracy. Detecting and precisely measuring this small difference in time is extremely important to measurement accuracy and each manufacturer has proprietary techniques to achieve this measurement. Velocity profiles are highly complex and one set of transducers only measures the velocity along a very thin path. To determine the velocity profile more accurately, custody transfer ultrasonic meters use *multiple* sets of transducers. The number of paths in multiple transducer configuration, their location, and the associated algorithms used to integrate the path velocities into an average velocity all contribute to the meter's accuracy. Therefore, an apparently easy system in reality is slightly more complex and highly dependent on all the factors discussed. Also swirl—transverse velocity due to piping configurations and local velocities at the transducer ports play a role in the path velocity. Fortunately, as the local velocities are normally symmetrical, they can be canceled statistically. The transverse velocity, if not eliminated by the flow conditioner, must be *accounted* for by the meter. To determine the true average velocity, ultrasonic meters measure the path and transverse velocities are sampled (unique for the meter model) many times a second and sent to the **microcontroller** of the control unit which provides the outputs for the volume that has passed through the meter. The greater the number of samples the better will be the accuracy. USFM measures the flow stream directly, without inertia and imposing any constraints. USFMs are more sensitive to systematic error than conventional meters. However, inertia-free measurement and pulse output delay due to sampling are **key** reasons behind the difficulties to prove ultrasonic meters with conventional provers [5].

2.4.2 FEATURES AND ADVANTAGES

The following are the major advantages and features available from USFM:

1. Nonintrusive (Some non invasive also) measurement;
2. No moving parts;
3. Bidirectional flow measurement;
4. No/minimal pressure loss;
5. High turndown ratio;
6. Capability to handle a wide range of fluids;
7. Extensive diagnostic features;
8. Easier installation;
9. Extensive diagnostic features and information on flow distribution make calibration easier and reduce measurement uncertainty;
10. Provide information on other fluid properties;
11. Capability for remote operation;
12. Available in a wide range of sizes, from 50 mm up to ~1050 mm.

2.4.3 APPLICATION AREAS

USFMs are most popular for the following major applications of CT:

1. High-volume natural gas transportation;
2. Crude oil production, including heavy crudes found in oil shale and oil sands, i.e., products with entrained solids or gas can attenuate;
3. Refined products and light crude oil; high volume: transportation and processing;
4. Pipeline applications;
5. Ship loading/unloading facilities especially in harsh environment;
6. Throughput applications.

2.4.4 USFM PERFORMANCE

The following are typical ultrasonic meter performance parameters:

1. **Range:** Flow (turndown) range: Any flow range from 10% to 100% of maximum flow rate [5];
2. **Viscosity:** Large range of viscosity; Reynolds number >20,000;
3. **Turndown ratio:** 60:1 with linearity around 0.15%;
4. **Factors affecting performance:** Meter performances specified above are also affected in the following ways:
   - Since highly viscous products may attenuate or block US signal, hence based on meter size, there is a maximum viscosity handling limitation as specified by the manufacturer
   - Ultrasonic meters are affected by boundary layer thickness. Multipath USFMs have methods to minimize this effect. Even with these compensation methods there is a transitional region where the velocity profile can change significantly under the same dynamic conditions [5].

2.4.5 PROVING LIQUID ULTRASONIC FLOW METERS

Field proving of liquid ultrasonic flow meters is difficult for the following reasons:

- The output pulse of USFM there is a time delay between measured parameter and the pulse output. So these are not related in "real time" to the meter throughput.
- Reducing the meter's response time and/or increasing the prove volume are recommended. As the measurement is inertia-free, it is very sensitive to systematic error.

Measurement accuracy is improved by taking more samples. In the new API Ultrasonic Flow Meter Measurement standard, prover volumes are recommended to achieve acceptable results. Also included are prover sizes for similar-size turbine meters.

2.5.0 Coriolis Type Flow Metering

In 2003, the AGA approved a report AGA-11 and in 2012 standard "Measurement of Single-Phase, Intermediate, and Finished Hydrocarbon Fluids by Coriolis Meters," on Coriolis flow meter use for natural-gas custody transfer. In 2002, the API approved the use of Coriolis flow meters in custody transfer and fiscal metering (API—Chapter 5.6).

2.5.1 PRINCIPLES OF OPERATION

Coriolis flow meters measure mass flow directly. Since in this meter, mass flow is measured utilizing Coriolis force it is called a Coriolis flow meter. Flow is measured using Coriolis meters by analyzing the changes in the Coriolis force of a flowing substance. There are two phenomena deployed to generate Coriolis force. These are: a

rotation force created through vibration of a flow conduit and a mass moving toward and away from the axis of rotation. This is achieved with the help of fluid moving through a tube that rotates about a fixed axis perpendicular to the centerline of the tube. As fluid flows through a Coriolis flow meter, the measuring tubes twist slightly due to the Coriolis force. The natural vibration frequency of the tubes changes with the mass flow of the fluid. With a fluid mass, the Coriolis force is proportional to the mass flow rate of that fluid. A Coriolis meter has two main components: an oscillating flow tube equipped with sensors and drivers, and an electronic transmitter that controls the oscillations, analyzes the results, and transmits the information.

2.5.2 METER SIZE

In spite of high accuracy, Coriolis meters have limitations on meter size. Coriolis meters get large and unwieldy once they reach the 6-inch size [6]. Even 3-inch and 4-inch meters are quite large. Coriolis meters are currently available from line sizes 1/14″ to 16″ (1−400 mm). Despite the challenges involved, suppliers over the past several years have manufactured larger sizes of Coriolis flow meters. Rheonik (GE Measurement) has long had large-line-size Coriolis meters. Now companies Endress + Hauser, Krohne, and Micro Motion have also come out with larger-size meters. Endress + Hauser and Micro Motion offer bent-tube meters, while Krohne's large-size meters are straight tube. Most of these meters are aimed at the custody transfer market for oil and gas applications [6].

2.5.3 CORIOLIS METER FEATURES

1. Coriolis mass flow measuring technology offers high accuracy and reliability in measuring material flow.
2. Coriolis flow meters can have high-pressure drop.
3. Available meter size is limited to 400 mm.
4. There are as such no moving parts and high accuracies outweigh the above disadvantages.
5. There is no requirement for upstream length.
6. In some applications it is considered the best flow-measuring technology.

2.5.4 CORIOLIS METER PERFORMANCE

For actual performance, the manufacturer data sheet should be consulted. However, typical performance of the meter is as follows:

Over the full range of 0%−100% high accuracy and linearity is possible.
Typical turndown of flow for which assured accuracy is possible is 10:1.
Viscosity turndown ratio: 10:1; however, it is guided by the pressure drop.
Zero stability: This is an important issue associated with the Coriolis meter. This is already discussed at length in Chapter VI, which may be referenced.

2.5.5 CORIOLIS METER CT APPLICATION AREAS

The following are the major application areas of Coriolis meters in custody transfer applications:

- Crude oil measurement in leased auto custody transfer;
- Transportation of liquefied natural gas (LNG), liquefied petroleum gas (LPG), and natural gas liquid (NGL);
- Marketing of LNG, LPG, and NGL;
- Transport or loading of any product with entrained particulates, as indicated for USFM.

2.5.6 CORIOLIS METER DISCUSSIONS

The following are a few issues which must be addressed for better performance.

Proper meter installation is very important. Also, it is important to establish an initial zero point adjustment under stable process conditions. These are important for in situ calibration when the meter is rezeroed and it is to be reproven [6].

Like USFM, Coriolis meter output pulses are also not instantaneous and hence not in "real time." There exists a time delay between the

measurement and the transmitted pulse/frequency output. An API task group has been formed to investigate these details.

We now investigate prover systems/master meters.

3.0.0 DISCUSSIONS ON PROVER SYSTEMS AND MASTER METERS

Custody transfer fluid flow meters are calibrated against a master meter at site, or in liquid metering applications, with the help of a meter prover which can be portable or stationary. Normally, for pipe sizes below 1050 mm (42 inch) it can be done at site. Larger-size pipes are often sent for calibration to a place with such calibration facilities. In this connection definitions of various terms as per API and International vocabulary of basic and general terms in metrology (VIM) are important. There are three types of proving:

- *Direct proving:* Best accuracy;*
- *Transfer proving:* Reduced accuracy* due to uncertainty* of master meter;
- *Master meter offsite proven:* Lowest accuracy* due to added systemic error caused by installation and operating conditions.

(* Refer to Table AIV/3.1.0-1 for the definitions.)

1. **Meter prover:** This is a calibration unit usually kept at site as part of a liquid metering system to

TABLE AIV/3.1.0-1 Definitions of Terms in API and VIM

Term	API	VIM
Accuracy	API (1.0): It is the ability of the measuring instrument to indicate values closely approximating the true value of the quantity measured	VIM 1995 (3.5): Closeness of the agreement between the result of a measurement and a true value of the measurand
Calibration	API Chapter 4 for prover: Calibration stands to mean the procedure to determine the volume of a prover. Proving is the procedure to determine the meter factor	VIM 1995 (6.11): this is the set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system and the corresponding values realized by standards
Error	API (4.9.1): Error is caused by differences between the metered volume and the true volume	VIM 2008 (2.16): Measured quantity value minus a reference quantity value
Error Types	API (13): Spurious error, random error, and systematic error (variable and constant)	VIM (3.1.3): Random error VIM (3.14): Systematic error
Meter Factor	API (Chapter 4): According to API Chapter IV meter factor is a ratio of prover's volume to meter indicated volume, i.e., $MF = \frac{\text{Prover volume}}{\text{meter indicated volume}}$	VIM 1995 (3.16): Correction Factor: numerical factor by which the uncorrected result of a measurement is multiplied to compensate for (systematic) error)
Meter Factor	**Influencing factors:** Flow rate, pressure, temperature, viscosity, contamination, wear, etc. **Condition statement:** Proving condition should match the operating conditions in flow, pressure, temperature and liquid characteristics API density and viscosity	
Uncertainty	API (13): This is the true value of a measurement that cannot be determined, but a valid estimator can be obtained by the statistical analysis. The range or interval within which the true value can be expected to lie is the uncertainty range	VIM 2008 (2.26): Non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used

compare the meter's registered throughput to a known reference volume. Prover types: There are different kinds of provers:

- Pipe prover;
- Tank prover;
- Compact prover.

A meter should be proved on consecutive runs and in repeated measures the tolerance must be below the declared repeatability. A pipe prover which is basically a long run pipe, has *known* internal volume for comparison. There are different types of pipe provers, including:

- Unidirectional;
- Bidirectional;
- Piston prover;
- Compact prover.

According to API a liquid flow prover is an open or closed vessel of known volume utilized as a volumetric reference standard for the calibration of meters in liquid petroleum service. This means it is a calibrated volume which is traceable to an internationally recognized measuring standard.

2. **Master meter:** In proving by master meter applications, one flow meter is designated as the flow prover. The meter must have an accuracy that is better (some claim one order of magnitude better, while others claim that four times better is necessary) than the meter to be tested. The master meter must also have been calibrated against a primary standard within the past 12 months [6]. The flow meter to be tested should be in series with the master meter prover. Based on the error, the correction factor is generated and programmed with a computing system.

3.1.0 Commonly Used Terms and Definitions

A few commonly used terms defined in API as well as in VIM, mainly in connection with meter proving have been elaborated in Table AIV/3.1.0-1.

1. **Uncertainty statement:** It is very important in meter proving. It is an estimate characterizing the range of values within which the true measured value of a quantity lies and how frequently the reading does lie within this range—confidence level. Custody measurement starts with verification or proving a meter to a repeatability of 0.05% with five runs. Statistically this is an uncertainty of: ±0.027% at a 95% confidence level [7].
2. **Meter proving:** As per API, when the meter is initially installed, meter proving should be frequent. When after frequent proving, it has been established that the meter factors for any given liquid are being reproduced within narrow limits, then the proving frequency can be reduced, if the factors are under control and the overall repeatability of measurement is satisfactory.

3.2.0 Prover Types

As indicated earlier, there are different kinds of provers.

3.2.1 PIPE PROVERS

Pipe provers provide a dynamic calibration method in a sealed system with high accuracy. These provers can be used as a part of a metering system or as the reference. It consists of a length of pipe fitted with switches along the length and the volume between the switches is known. A displacer is introduced to the flow, the time it takes to travel between the switches gives a measure of the flow rate. The switches are used to gate a pulse counter, totalizing pulses from a flow meter, a measure of the meter factor can be found.

A key component of the prover is a displacer, which is a sphere made up of an elastomeric material. The sphere is filled with liquid and pressurized to inflate the sphere slightly larger than the pipe bore so that when the sphere is inserted into the pipe it takes up an elliptical shape for good seal to the pipe wall. The internal surface of a long steel pipe with a smooth bore is usually coated with epoxy resin to provide a smooth low-friction lining and to protect against corrosion. As the prover requires long length, for practical purposes, a loop is constructed in such a

way that the radius of the bends allow the sphere to pass without either sticking or leakage. At each end of the calibrated length of pipe a detector switch is located through the pipe wall. This usually takes the form of a plunger triggering a switch when the sphere passes under it. In this connection Fig II/2.4.1.2-2 B & C may be referenced.

There are two kinds of provers:

1. **Unidirectional pipe prover:** As the name implies, a unidirectional prover has a displacer which only travels in one direction along the pipe.
2. **Bidirectional pipe prover:** To reduce the length of the pipe bidirectional pipe, provers are used. In this method, with the help of a four-way valve, flow can travel in both directions.

3.2.2 PISTON PROVER

Piston types are used for difficult fluids which may damage the lining material. These are straight and quite long. The pipe is normally a smooth-honed bore pipe of stainless or plated carbon steel. The displacer is a piston with multiple seals. Switches are either plungers or noncontacting types. These are bidirectional, with the four-way changeover valve normally located midway along the pipe length to equalize the inlet and outlet pipe work. These are also called compact provers.

3.2.3 SMALL-VOLUME PROVER

This is basically a commercially available pipe prover with a volume about one-tenth of a conventional design. These are meant for PD meters, liquid USFMs, Coriolis, and turbine meters (most popular), custody transfer, production FPSO, etc. They are usually meant for flow rates up to 4000 m^3/h and can be used for any flow meter with a pulse output. There are several types of small-volume provers (SVM), such as offshore SVMs, stationary SVMs, truck/trailer-mounted SVMs, etc.

3.3.0 Proving Conditions

It is important to prove at conditions that are as similar as possible to the expected operating conditions. The major influencing factors are described here:

1. Stable flow rate, density, temperature, and pressure are important, so system design, prover settings, and maintenance are critical for proving.
2. Minimizing the pipe length between the meter and prover and avoiding dead-end branches. To ensure measurement traceability, reproducibility, and repeatability should be well maintained (refer to API MPMS Chapter 4 and Chapter 21.2).
3. Sufficient back pressure to be maintained to avoid vapor breakout and to maintain a stable flow rate during displacer launch and travel (refer to API MPMS Chapter 5.6).
4. Accurate density measurement is crucial (refer to API MPMS Chapter 14.6).
5. Enabling compensation for the effect of pressure on the meter.

Custody transfer measurement with prover has been depicted in Fig AIV/1.0.0-1. In this connection relevant part of section 2.4.0 and Fig II/2.4.1.2-2 of chapter II may be referenced. With these short discussions on custody transfer including the proving system coming to an end a brief idea is gained on custody-transfer issues. Since custody transfer in oil and gas is critical and crucial there have been developments in all directions. Therefore, it is a subject by itself and it is not really feasible to completely cover the same in this book. It is therefore recommended that the reader should familiarize themselves with the governing standards and apprise themselves with newer developments.

Although the safety lifecycle deals with electrical and electronic aspects of safety, it is an important aspect for engineers of all disciplines, especially for instrumentation and process engineers. There are two sides to look into the issue of safety lifecycle, one from the manufacturer's point of view (IEC 61508) and the other from the end-user's point of view (IEC 61511). In Appendix V both will be covered in brief.

FURTHER READING

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APPENDIX V

SAFETY LIFECYCLE

PREAMBLE

*This appendix has been intended to give an idea to the reader about safety lifecycle, which has become part and parcel of all plants and industry as a safeguard against loss of property, personnel, and environment. This appendix has mainly been developed from my book entitled "**Plant Hazard Analysis and Safety Instrumentation Systems**" (AP—Elsevier & IChemE U.K.), which deals with detailed analysis of plant hazards and suggested safety instrumentation as a safeguard against that. It is discussed at length there. In this limited space very brief discussions pertinent to safety lifecycle as per IEC 61508 and IEC 61511 only have been presented. In order to give an idea of this factor, properly relevant issues have been touched upon. The interested reader may refer to Ref. [1].*

1.0.0 GENERAL DISCUSSIONS

Assets are normally acquired against a lot of effort, toil, and monetary cost; people always wish to protect their assets. Unfortunately, this is not always possible on account of hazards in various forms, however plans to take safety measures are usually made. Until recently, in the process industry, people would incorporate the necessary safety measures in the form of protections under basic process control systems (BPCSs). In the arena of industrial hazard and risk analysis, "system" is defined as a subject of risk assessment, which includes mainly process, product, facility, and environmental and logical groups. Therefore, safety associated with it needs to be treated separately from BPCSs. Sometimes people incorporate redundancy in the system design so that, in case of the failure of one, there will be others available as backups, that is, to fall back on. This is not always true, as is the case with common cause failure. After 1995, people felt the need for integration of safety systems with BPCSs, without compromising the functional *independence* between the two, to get the best secured industrial systems. In order to treat these independently in a standardized manner, several international standards—IEC 61508, IEC 61511, ISA 84—evolved [1]. These standards, especially IEC 61508 and IEC 61511, are backbone standards of safety lifecycle. These standards are meant

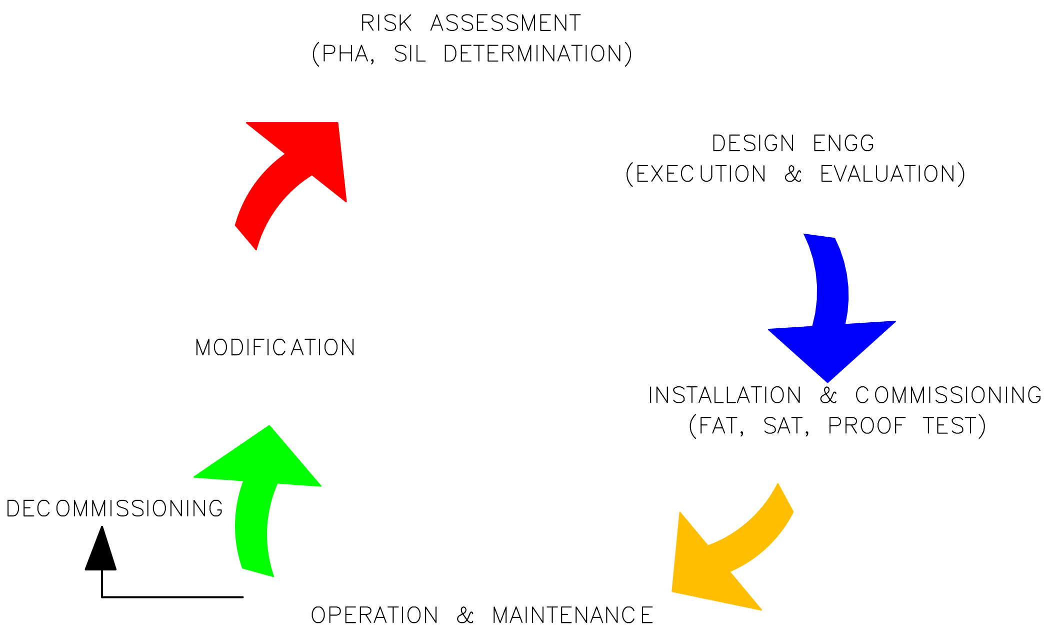


FIGURE AV/1.0.0-1 Safety lifecycle of SIS [1].

for electrical, electronics, and programmable electronics (E/E/PE). These standards have been developed with the aim that at process upset, or system or equipment failure, the designed system would allow the process *safety* to be managed in a systematic way following a risk-based management system. Safety instrumented systems (SISs) play a great role in mitigating technical risks in industrial plants. An **SIS** consists of a well-engineered hardware and software control system used to monitor the condition of plant within the operating limit. When any risk condition arises, it triggers an alarm and takes the entire system to a safe condition to mitigate all kinds of risks as far as possible.

[The safety life cycle, according to IEC standard, can be considered as a cyclic process or closed loop comprising in cyclic fashion of ***identify—analyze—design—verify*** *and is comparable with "****plan, do, check, act****" of ISO 31000.]*

In view of this, the SIS lifecycle can be conceived of as what is shown in Fig. AV/1.0.0-1.

Unless protected, a system runs at a risk. This is an inherent risk prior to any action being taken to change the consequence. Designers aim to bring the system within, or in fact below, that risk limit by incorporating various protection measures to mitigate the risk. Even after such protection, the small risk left is often referred to as the residual risk. Some protections come from other technological means, but major protections come through the interface of BPCS with a safety system to make SIS. Readers should not confuse the operational interlock and protections of BPCS, with SIS. The concept has been clarified through Fig. AV/1.0.0-2.

Prior to moving on to other discussions, it is important that a few terms are defined.

1.1.0 Definitions and Explanations of a Few Related Terms

A few terms normally encountered in safety lifecycle discussions are clarified here.

1. **Hazard:** The term hazard has been defined by many agencies in different ways, based on their terms of reference. These are detailed in Ref. [1], interested readers may refer to the same. Here only two definitions have been defined:
   - *General definition:* Hazard can be considered as a state with a set of conditions of a system, which together with other conditions in the environment, or in the

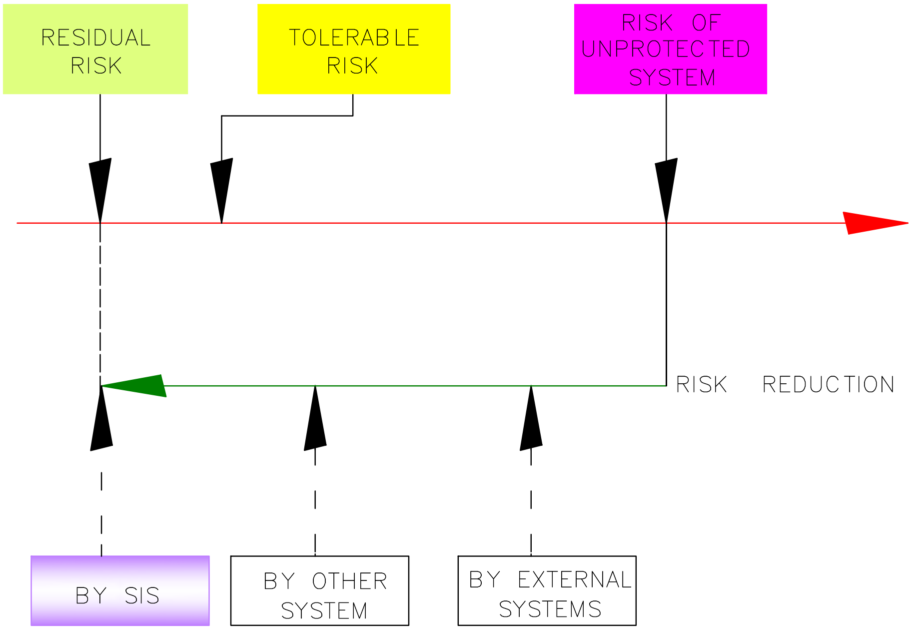


FIGURE AV/1.0.0-2 Risk reduction by SIS. *Based on standard IEC 61508 Concept.*

environment of the system, will lead to an accident. So, a hazard can be any biological, chemical, mechanical, environmental, or physical agent which has the potential to cause harm or damage to humans, other organisms, plant, machinery, assets, or the environment, in the absence of its control.

- *ISO/IEC Definition:* As per ISO/IEC 51 or IEC 61508, a hazard is defined as, "the potential source of harm." In IEC 61508, harm has been defined as physical injury or damage to the health of people either directly or indirectly as a result of damage to property or to the environment.

2. **Hazard analysis:** Hazard analysis uncovers the hazards that exist in the workplace (in this case, industrial plant) focusing on the system or project. By hazard analysis, risk-based decisions are taken to develop means to quantify, track, develop mitigation means, and control hazards, follow-up action, verify effectiveness, and communicate.
3. **Risk:** According to ISO/IEC guide 51/IEC 61508, risk is, "the combination of probability of occurrence of harm and the severity of that harm." From here it transpires that risk refers to the likelihood that a hazard can cause actual damage.
4. **Basic process/plant control system (BPCS):** This system handles the process controls and monitoring for the process. According to IEC 61511, "BPCS is a key layer of protection which responds to input signals from the process, its associated equipment, other programmable systems and/or operator and generates output signals causing the process and its associated equipment to operate in the desired manner but which does not perform any safety instrumented functions with a claimed SIL 1."
5. **Safety instrumented system (SIS):** SIS is designed to prevent, or mitigate from happening, a hazardous event, by taking the process to a safe state whenever a predefined or predetermined condition occurs to the system. It is a combination of sensors, logic solvers, and final control elements. These are in programmable electronics (PE), consisting of both hardware and software.
6. **Safety instrumented function (SIF):** SIF consists of sensors, logic solvers, and final control element combinations. SIF takes the

system or process into the safe zone in the event of a hazardous situation/event, which is determined by predefined conditions for the process.

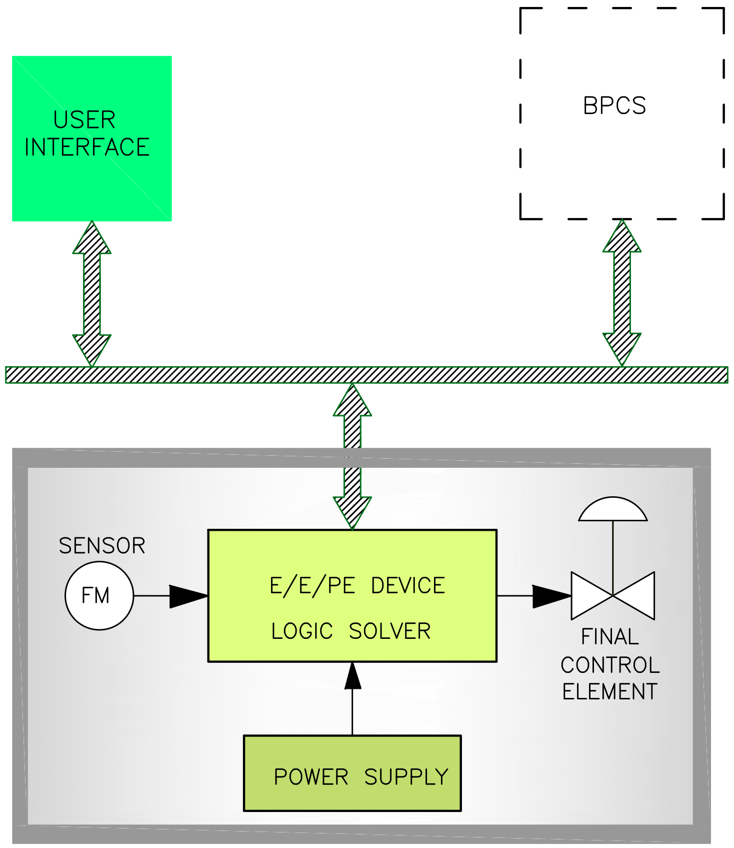
7. **Functional safety:** According to the ISA, "the ability of SIS or other means of risk reduction to carry out the actions necessary to achieve or to maintain a safe state for the process and its associated equipment." Also, functional safety in SIS highly depends on proper functioning of sensors, logic solvers, and Final control element (FCE), so that a reduced risk level can be achieved.
8. **Safety integrity level (SIL):** This is a measure of the performance of an SIS. It is determined by Probability of failure on demand (PFD) for SIF (SIS). There are four SIL levels represented by numbers: SIL 1, 2, 3, 4. The higher the SIL number, the better will be the performance and the lower will be the PFD value. However, with an increase in SIL number, the cost and complexity of the system increases, but the risk level reduces. It is worth noting that there can be an individual component PFD but not SIL. SIL is only given to a system (SIS). SIL certification can be issued by the company (self-certification allowed), or other competent authority to indicate that appropriate the procedure, analysis, and calculation have been followed and are compatible for use in appropriate SIL level.
9. **Probability of failure on demand (PFD):** This is the probability that SIF/SIS fails to perform its intended safety function during a potentially dangerous condition. PFDavg is normally used in calculations when regularly inspected and tested.
10. **Some other associated terms:** The following terms are important and associated with hazard and risk analysis:
    - *Accident:* This is an undesired, unplanned (but may not always be unexpected) event, which will result in a specified level of loss (in terms of health, property, production, etc.);
    - *Mishap:* This is bad luck, misfortune, etc. In terms of industry, it could be an accident, which is associated with uncontrolled release of energy and toxic material exposure;
    - *Near miss/incident:* This is normally used in a good sense, meaning an event occurred, but it involved very minor or no loss (in terms of health, property, production, etc.);
    - *Safety:* Freedom (or nearly freedom!) from accident or loss.

1.2.0 Discussions on BPCS and SIS

In this section an overview of the interrelation amongst BPCS, SIS, SIL, and functional safety will be covered. As indicated earlier, like BPCS, SIS also consists of sensors, final control elements, and logic solvers. A typical layout has been shown in Fig. AV/1.2.0-1.

In this diagram, the user interface and interface with BPCS have been shown through a communication bus. It is interesting to note that there can be separate BPCS and SIS, but these two can be integrated as long as they meet the requirements of standards like IEC 61508/61511 or ANSI/ISA 84. Functional safety is very important for the safety lifecycle, as covered below.

1. **Functional safety concept:** Basically, functional safety stands on the following concept:
    - All processes or manufacturing systems have inherent hazard;
    - All processes or manufacturing systems have an inherent quantifiable failure rate, which cannot be brought to zero value;
    - All processes or manufacturing systems have a tolerable failure rate without causing any harm to the system. Also, this failure rate is specific to the system in question;
    - For all processes or manufacturing systems, these failure rates can be categorized in terms of SIL (from functional safety point of view).



DOTTED BPCS SIGNIFIES THAT IT COULD BE INTEGRATED WITH SIS.

DOUBLE WALLS SHOW SIS PROTECTION LAYER

FIGURE AV/1.2.0-1 SIS boundary and layout.

2. **Failure category:** The failure categories in a functionally safe system are described here:
   - *Systematic failure:* Systematic failure may come from a shortcoming in system design, implementation, or manufacturing defect, or for not following of any statute, standard, or good engineering practice. These can be reduced thorough analysis and remedial measures.
   - *Random failure:* These are uncontrolled, unnoticed failures, sometimes inherent with the process and they cannot be reduced in a systematic way, only proper attention given to early detection can reduce the amount of loss (e.g., unprecedented grid collapse). Safety function may come as a result of hazard analysis and it is to be implemented in SIS.

   We now look into risk analysis in more detail.

2.0.0 RISK DISCUSSIONS

Prior to taking up the risk analysis issue it is better to address some pertinent issues associated with risks and risk analysis.

2.0.1 RISK FREQUENCY

This defines the likelihood of the risk, that is, it stands for the probability of risk. These are categorized as:

Very likely: at least once in 6 months;
Likely: at least once a year;
Unlikely: maybe once in lifetime
Very unlikely: May be 1%.

Typical examples are shown here. Risk frequency data and release data are available in HSE (UK), OREDA, and OGP publications.

2.0.2 SEVERITY

Severity is loosely used to indicate the impact of risk, that is, the consequence. These are slightly harmful (e.g., superficial cut, minor cut, etc.), harmful (e.g., burns, serious pains, minor fracture), and extremely harmful (e.g., major fracture, amputation/permanent damage or even death). There are some other ways to categorize severity. Typical categorizations could be as listed here:

1. **Minor:** Minor system damage without causing injury;
2. **Major:** Low-level exposure to personnel, activates public alarm;
3. **Critical:** Minor injury to personnel, fire, or release of chemical to environment;
4. **Catastrophic:** Major injury, death, big leakage (e.g., Bhopal gas leak).

2.0.3 RISK LEVEL (BASED ON ACTION AND TIME)

The levels of risks are often categorized based on the potential. The categories are termed as follows:

1. **Very low:** These risks are acceptable and may not need any action;
2. **Low:** No control may be necessary unless these are available at low cost;
3. **Medium:** Suitable considerations shall be there to see if the risk can be lowered, wherever applicable, to a tolerable level, within a defined time limit. However, due considerations shall be given to the additional cost for risk reduction. Whenever the risk is associated with harmful consequences, it is necessary to make sure that risk reduction controls are properly maintained;
4. **High:** A good amount of effort is applied to reduce risk on an urgent basis within a defined time frame. It is essential to give due considerations towards the choice amongst suspending or restricting the activity or applying an interim control measure until the main risk reduction control is implemented. Whenever the risk is associated with a harmful consequence, it is necessary to make sure that risk reduction controls are properly maintained;
5. **Very high:** Unacceptable. Substantial improvements in risk reduction control measures are necessary to reduce the risk to an acceptable level. Activities need to be halted until risk reduction control is implemented. Otherwise, work shall remain prohibited. It is essential maintain the control system for risk reduction extremely with care (as without such control, systems may not be permitted to function).

Risk associated with very harmful consequences needs risk assessment and analysis. The above categorizations are qualitative in nature. For quantitative calculations, one may need the help of probability and associated software, which are also available from various agencies for different applications. Interrelations amongst these factors have been depicted in Fig. AV/2.0.0-1.

2.1.0 Risk Analysis and Assessment

For plant hazard analysis there will always be a risk target, which is a measure that expresses the consequence of a risk in relevant terms of the project and organization concerned. In order to get the measure it is necessary to go for risk analysis and risk assessment. *What is risk analysis?*

1. **Risk analysis:** As per the latest version of IEC/ISO 31010 (IEC 60300-3-9), risk analysis is the "systematic use of available information to identify hazard and to estimate the risk to individuals, populations, property or

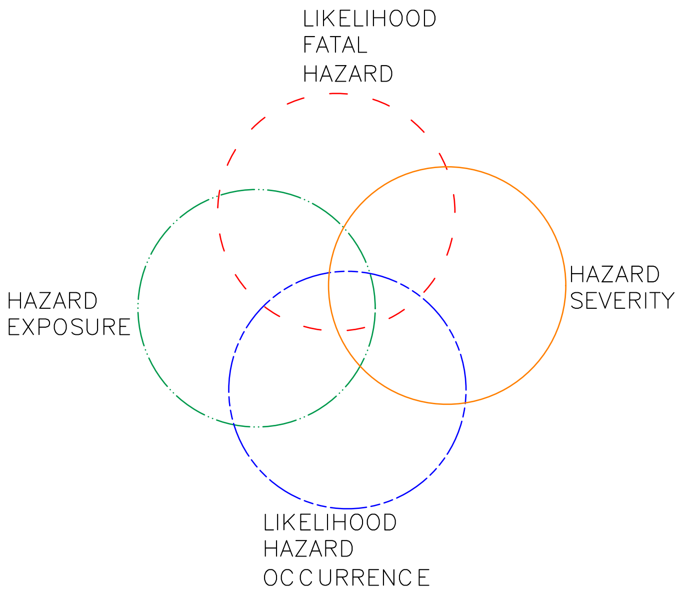


FIGURE AV/2.0.0-1 Combinations of risk component.

the environment." So, essentially, risk analysis finds, organizes, and categorizes sets of risks.

2. **Risk assessment:** Risk assessment will be clarified from the following activities:
   - Identification of hazard;
   - Analysis and evaluation of risk;
   - Finding an appropriate way to control and mitigate hazards;
   - The main aim of risk assessment is to remove hazard, or reduce the risk level by adapting necessary control measures, to move towards safety.
3. **Risk assessment procedure:** The following points are major issues considered as part of the risk assessment procedure:
   - Hazard identification;
   - Evaluation of risk in terms of; likelihood, severity, and level of risk;
   - Standard operating conditions;
   - Emergency situation (nonstandard operation);
   - Review of all associated information;
   - Actual and potential exposure of personnel (latency, frequency, intensity);
   - Environmental impact;
   - Design engineering control;
   - Documentation.

Risk register, risk matrix, etc. are tools for risk analysis and assessments.

2.1.1 RISK REGISTER

A typical risk register has been depicted in Fig. AV/2.1.0-1.

A risk register is basically a record of identified risks for a project. The major characteristic

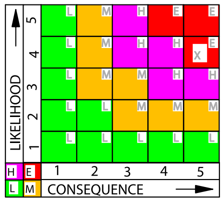
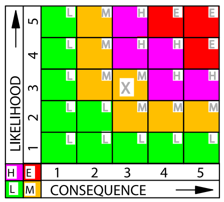
RISK IDENTIFICATION									QUALITATIVE RISK ASSESSMENT			RISK RESPONSE ACTION			RISK MONITORING & CONTROL	
SERIAL NO.	RISK ID.	STATUS	CATEGORY	EVENT DETAILS	CAUSE DETAILS	EFFECT DETAILS	+ OR - IMPACT	PRIMARY OBJECTIVE	LIKELIHOOD	CONSEQUENCE	RISK MATRIX (L: LOW) (M: MEDIUM) (H:HIGH) (E:EXTREME)	STRATEGY	ACTION DETAILS	RESPONSIBLE PERSON	INTERVAL	STATUS REVIEW COMMENTS DATE
01	PRF 001	ACTIVE	EXTERNAL	PROJECT FUND PART LOAN NOT RELEASED IN TIME	BUDGET CONSTRAINT ALLOCATION CHANGED CURTAIL IN INTERIOR	PROJECT DELAY	(-) IMPACT	TIMING	HIGH	VERY HIGH		MITIGATE	PHASING IN PLANNED ALLOTMENT. HENCE WORK PHASED OUT	CHIEF PLANNING ENGINEER AND FINANCE OFFICER	MONTHLY	BANK FOLLOW UP WITH GOVT. LICENCE FINAL DEADLINE DATE DD.MM.YYYY
02	PSC 001	ACTIVE	CONSTRUCTION	UNIDENTIFIED UTILITY TRANSPORTATION COST	ADDITIONAL CABLE COST AND LAYING COST	ADDITIONAL PROJECT COST IMPACT	(-) IMPACT	COST	MEDIUM	MEDIUM		MITIGATE	PURSUE WITH UTILITY COMPANY FOR ALTERNATE ROUTE	ELECTRICAL ENGINEER	MONTHLY	LETTER TO UTILITY COMPANY DD.MM.YYYY

FIGURE AV/2.1.0-1 Risk register (typical).

features of a risk register have been listed below:

1. Short description of each risk along with associated consequences;
2. Factors influencing the likelihood and impact;
3. Grading of risks e.g., low, medium, high, extreme, etc.;
4. Risk acceptability;
5. Existing and proposed actions for risk mitigation;
6. Key risk indicator (KRI) and upward reporting factor.

2.1.2 RISK MATRIX

The risk matrix may be considered as a quantitative or semiquantitative tool for qualitative hazard analysis. It is very important to develop a risk matrix design very precisely so that there will not be a false sense of security after the risk matrix is done. If the likelihood or impact of any risk is not properly defined, then as a result of wrong calculation any particular risk may be considered in the low-risk level, but in reality it is not so. In that case one may be happy to note that it is low level and hence secured—a false sense of security.

There are several standard guidelines and published risk matrices, but at the start one has to decide the purpose for which it is to be developed. Table AV/2.1.0-1 is an example of a risk matrix available from the Center for Chemical Plant Safety (CCPS). Here, risk levels are described as I, II, III, and IV. Tables AV/2.1.0-2 and AV/2.1.0-3, which are self-explanatory, show various features of risk matrices. They also show how a risk matrix can be qualitative as well as quantitative. Consequence range has been explained in Table AV/2.1.0-5.

Here it is to be noted that both frequency as well as consequences are quantified. However, frequency and consequence can be qualitative also.

TABLE AV/2.1.0-1 Risk Matrix

	Consequence			
Frequency	**1**	**2**	**3**	**4**
4	IV	II	I	I
3	IV	III	II	I
2	IV	IV	III	II
1	IV	IV	IV	III

TABLE AV/2.1.0-2 Risk Level. Likelihood and Consequence Ranges Have Been Explained in Tables AV/2.1.0-3 and AV/2.1.0-4

Risk Level	Category	Description
I	Unacceptable	Should be mitigated engineering and/or administrative control to risk level III or less, within a specified period (say 6 months)
II	Undesirable	Should be mitigated engineering and/or administrative control to risk level III or less, within a specified period (say 12 months)
III	Acceptable with controls	Should be verified that procedures and controls are in place
IV	Acceptable	No mitigation required

TABLE AV/2.1.0-3 Likelihood Ranges Based on the Levels of Protection

Likelihood Range	Quantitative Frequency Criteria (Typical)
Level 4	Initiating event or failure (e.g., leakage/rupture)
Level 3	One level of protection (e.g., pipe leakage, overload)
Level 2	Two levels of protection (e.g., electrical actuator uprooting)
Level 1	Three levels of protection (e.g., vessel failure)

TABLE AV/2.1.0-4 Consequence Range

Consequence Range	Quantitative Safety Consequence Criteria
4	Onsite/offsite: potential for multiple life-threatening injuries or fatalities
	Environmental: uncontained release with potential for major environmental impact
	Property: (including plant): plant damage value in excess (e.g., $)100M unit of currency
3	Onsite/offsite: potential for single life-threatening injury or fatality
	Environmental: uncontained release with potential for moderate environmental impact
	Property: (including plant): plant damage value in the range of (e.g., $)10–100M unit of currency
2	Onsite/offsite: potential for an injury requires medical attention
	Environmental: uncontained release with potential for minor environmental impact
	Property: (including plant): plant damage value in the range of (e.g., $)1–10M unit of currency
1	Onsite: potential for injuries requires only first aid
	Offsite: noise or odor
	Environmental: contained release with local impact only
	Property: (including plant): plant damage value in the range of (e.g., $) 0.1–1.0M unit of currency

As stated earlier, risk matrices could be qualitative, semiquantitative, or quantitative. A typical quantitative risk matrix has been shown in Table AV/2.1.0-5.

Qualitative frequency terms include the following:

- Frequent;
- Probable;
- Occasional;
- Remote;
- Improbable;
- Incredible.

Similarly, qualitative consequences include the following:

- Catastrophic;
- Critical;
- Marginal;
- Negligible.

Now look at Table AV/2.1.0-5, and note that when either frequency or consequence sets of

TABLE AV/2.1.0-5 Quantitative Risk Matrix

	Consequence			
Probability	**$1000**	**$10,000**	**$100,000**	**$1,000,000**
Every month	Medium	High	High	High
Every year	Low	Medium	High	High
Once in 10 years	Negligible	Low	Medium	Medium
Once in 100 years	Negligible	Negligible	Low	Low

values are replaced by a qualitative set of values mentioned above then the matrix would be semiquantitative. Similarly, when both frequency and consequence sets of values are replaced by a qualitative set of values, the risk matrix would be qualitative as in Table AV/2.1.0-5.

We have concluded the discussion on risk analysis and now look at what is needed by standard IEC 61508 and 61511 for safety lifecycle.

3.0.0 SAFETY LIFECYCLE

The safety lifecycle for any system is based on IEC 61508, IEC 61511, and ISA 84.1. These standards are applicable for Electrical, Electronic and Programmable electronic (E/E/PE) equipment only. Since each equivalence with IEC standards so, they are not discussed separately. IEC 61508 is basically meant for manufacturers and 61511 is basically meant for end users. As a result, they have different approaches, so we take up each of them separately. One thing common to all of these is that each of them has three stages and these are: analysis, implementation/realization, and operation. A basic idea about safety lifecycle can be gained from Fig. AV/3.0.0-1. In addition, there will be a planning and management section. Of all stages, verification is most important. For a detailed explanation and interpretation of entire process Ref. [1], may be referred to.

Conceptually, a safety lifecycle can be represented as a cyclic system [2]. This has been shown in Fig. AV/3.0.0-1.

With this concept in mind, safety lifecycle discussions have been presented below. With the permission of IEC, the safety lifecycles of IEC 61508 and IEC 61511 have been reproduced as Figs. AV/3.0.0-2 and AV/3.0.0-3, respectively.

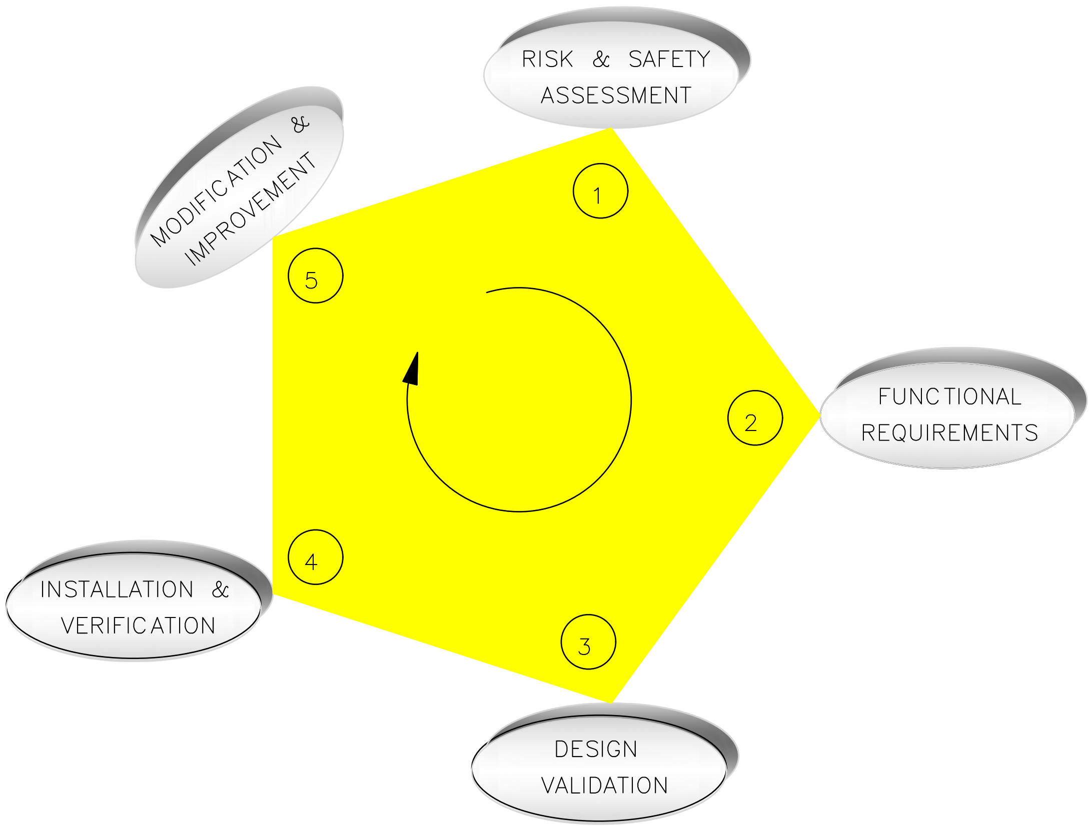


FIGURE AV/3.0.0-1 Concept of safety lifecycle.

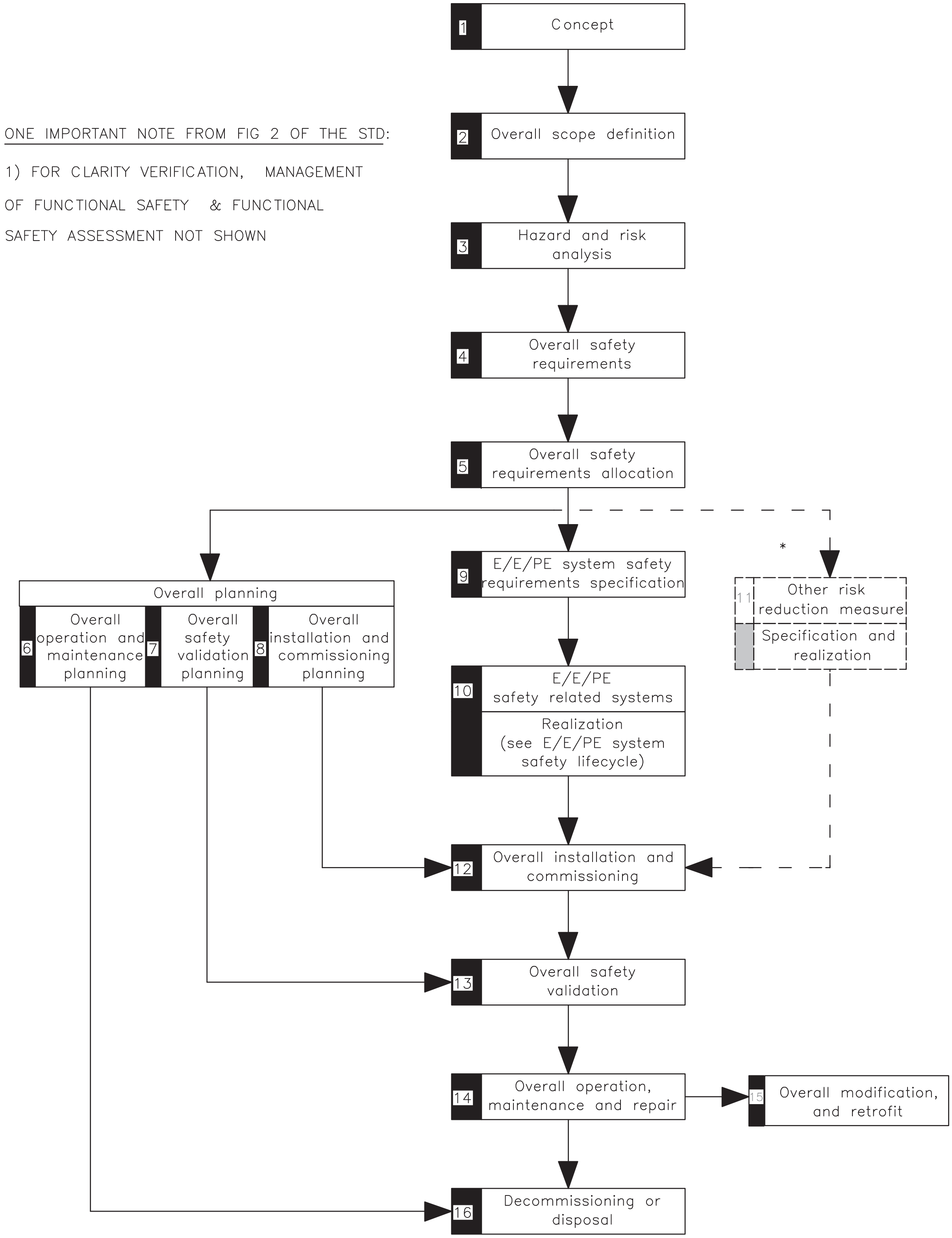


FIGURE AV/3.0.0-2 Safety lifecycle—IEC 61508 (Fig. 2). Refer to Fig. 2 of IEC 61508-1:2010. *Courtesy: IEC (see the detailed acknowledgment at the start of this appendix).*

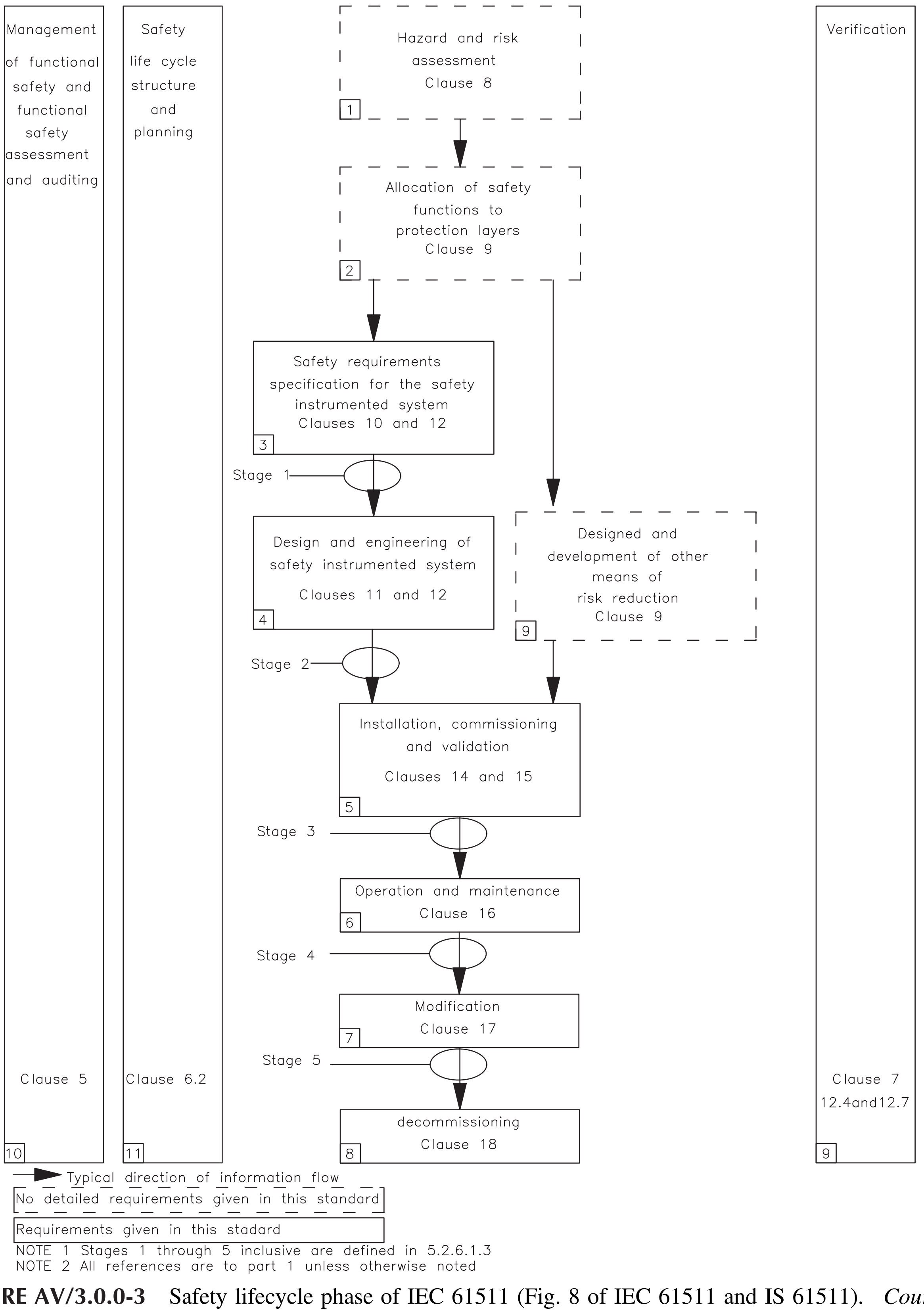


FIGURE AV/3.0.0-3 Safety lifecycle phase of IEC 61511 (Fig. 8 of IEC 61511 and IS 61511). *Courtesy: IEC (see the detailed acknowledgment at the beginning of this appendix).*

3.1.0 IEC 61508 Safety Lifecycle

As indicated above there are three stages, we start with the analysis part.

3.1.1 ANALYSIS PART OF IEC 61508

The following stages are under the analysis part.

Concept: Understanding of the equipment under control and its environment (physical and legal) to determine hazard sources and hazard information—Hazard interaction with other equipment.

Overall scope definitions: Here the system boundary and hazard scopes are defined.

Hazard and risk analysis: Here a list of hazards and events is prepared in sequence. It is followed by finding the likelihood and consequence (refer to Section 2.1.0).

Safety reallocation: This includes the overall safety requirements and safety reallocation.

3.1.2 ANALYSIS PART OF IEC 61508

This section deals with technology and architecture selections. The major issues are listed here:

- Perform reliability and safety evaluation to determine if you met your target SIL requirement;
- Conceptual design of SIS;
- Detailed design of SIS;
- System development, includes detail design and engineering, installation planning, installation, commissioning, including acceptance tests.

It is worth noting that there are two parts associated with the Programmable electronics (PE) system for realization/implementation; these are hardware (HW) and software (SW) implementation parts, including specification of safety requirements, safety integrity for each of HW and SW. There should be proper means to validate the planning, design development, and integration of each of HW and SW and complete system/overall validation. This stage also includes installation and commissioning of the entire safety system.

3.1.3 OPERATION PART OF IEC 61508

This really starts with the design validation through operation and maintenance to check whether the system really addressed the safety issues. Necessary modifications, including overall modification and retrofitting, as applicable, to be carried out to verify proper implementation, i.e., review of safety lifecycle activities and ensures that all steps were carried out and documentation is in place [3]. The final step is decommissioning or disposal.

The system has been described here very briefly. It is recommended to refer to Section 4 of Ref. [1] for detailed discussions and treaties.

3.2.0 IEC 61511 Safety Lifecycle

Basically this is management of functional safety and safety assessment with safety lifecycle structure and planning. Here safety life cycle is seen from user's point of view. The system is completed with proper verification. Here also there are three stages, i.e., analysis, implementation, and operation.

3.2.1 ANALYSIS PART OF IEC 61511

The basic structure of the analysis part consists of the following:

1. Hazard and risk assessment (Clause 8);
2. Allocation of safety function protection layer (exists around BPCS in different forms as additional protection to the system) (Clause 9);
3. Specification of SIS as safety requirement. Of these, Subsections 3.2.1.1 and 3.2.1.2 are not really part of the IEC standard but external things to interface (refer to clauses 8 and 9 of the standard).

3.2.2 IMPLEMENTATION PART OF IEC 61511

The basic structure of the implementation part consists of the following:
Design and engineering of SIS;
Design and development of other means of risk reduction (clause 9 not part of standard);
Installation, commissioning, and validation.

3.2.3 OPERATION PART OF IEC 61511

This stage starts after the erection and commissioning are over. The stages include:

Operation and maintenance;
Modification (as required);
Decommissioning.

Throughout all stages there will be verification which the end user needs to verify to establish the safety system.

The basic requirements for the lifecycle have been established. However, as far as flow metering is concerned the main issue is around SIS and SIL. Naturally, without discussions on SIS and SIL the discussions will be incomplete. Therefore, the discussions will be completed with the discussions on SIS and SIL in next section.

3.2.4 SUMMARY

From the above discussions it is clear that in each of the stages there will be some functions to be performed and these have been summarized below.

1. **Analyzing phase:** The following are the major steps:
   - Experiment design;
   - Hazard identification;
   - Risk assessment;
   - Comparison to risk tolerance criteria;
   - Risk reduction allocation;
   - Safety function definition;
   - Safety function specification;
   - Reliability verification.
2. **Implementation phase:** The following are the major steps:
   - Equipment design;
   - Software configuration;
   - Equipment build (IEC 61508);
   - Factory acceptance testing (IEC 61508);
   - Construction/installation;
   - Site acceptance testing;
   - Validation;
   - Training;
   - Pre-startup safety review.
3. **Operation phase:** The following are the major steps:
   - Operation;
   - Training;
   - Proof testing;
   - Inspection;
   - Maintenance;
   - Management of change;
   - Decommissioning.

4.0.0 SIF, SIL, AND SIS

Flow meters also need to be safe. As has been discussed earlier, there are several safety instrumented functions (SFI) in any safety instrumented system (SIS) comprising of sensors, logic solvers, and final control elements. Basically, flow meters are sensors in the SIS family. However, metering pumps at times can be the final control element in SIS (e.g. dosing system). Since discussions on the complete safety loop are beyond the scope of this book we need to concentrate on safety functions of individual items. This is more related to the safety integrated system (SIL). So our discussions will be mainly on the same.

SIS explanation and interrelation between SIS and SIF in line with IEC 61511-1:2003, have been depicted in Fig. AV/4.0.0-1 for better understanding.

Terms like SIS, SIF, and SIL have been discussed in Section 1.1.0 already. Let us now look at the relevant details.

1. **Safety instrumented system (SIS) explanation:** SIS is meant to prevent, control, or mitigate hazardous events and take the process to a safe state when predetermined conditions are violated. An SIS can be one or more SIFs, which is composed of a combination of sensors, logic solvers, and final control elements. SIS or SIF is extremely important especially when there is no other noninstrumented way of adequately eliminating or mitigating process risks.
2. **Safety integrity level (SIL) explanation:** In the context of the book, SIL basically represents to what extent a device or devices in

According to IEC 61511 *Safety instrumented control function* stands for safety instrumented function with a specified SIL operating in continuous mode which is necessary to prevent a hazardous condition from arising and/or to mitigate its consequences. *Safety instrumented control system* is instrumented system used to implement one or more safety instrumented control functions. Also *Safety instrumented system (S1S)* is instrumented system used to implement one or more safety instrumented functions (SIF). An S1S is composed of any combination of sensor (s), logic solver (s), and final elements(s)

FIGURE AV/4.0.0-1 SIS details as per IEC 61511-1:2003.

combination in process can be expected to perform safely. And, in the event of a failure, to what extent the process be expected to go to the safe state! Therefore, SIL gives a measure of safety risk or risk reduction to a tolerable limit for a given process. The IEC 61,508 standard also specifies the measures; such as "fault avoidance" (systematic faults) and "fault control" (systematic and random faults); to be taken into consideration in the design of safety functions consisting of a sensor, logic solver, and final control element. From IEC 61,508 one knows that SIL depends highly on two major factors: hardware failure tolerance (HFT) and safe failure fraction (SFF).

3. **Hardware failure tolerance (HFT):** This is the ability of hardware to continue to perform a specified safety function in the presence of faults or errors. HFT of N means that N+1 faults will cause a loss of safety function for the unit.
4. **Safe failure fraction (SFF):** This is the ratio of the average failure rates, safe plus dangerous detected failure, and safe plus dangerous failure (Ref: IEC 61508).

   Now let us look into SIL more closely.
5. **Probability of failure on demand (PFD):** PFD_{avg}: Probability of failure on demand is the *probability* of a functional unit or system *failing* to respond to a *demand* for action arising out of a potentially hazardous condition, i.e., a device will fail to perform its specified safety function *when it is asked* to do so. In other words the probability average PFD_{avg} is used in calculations for system reliability. When there is a probability of failure, then there has to be a question about its availability.
6. **Availability:** Availability is defined as the probability that equipment will perform its task.

   Now let us look into SIL more closely.

4.1.0 Safety Integrity Level (SIL) Discussions

As per IEC 61511, each SIF shall have an associated SIL, which is a measure of safety system performance and is related to the probability of failure on demand (PFD) for the associated SIF. There are four defined SILs: SIL-1, 2, 3, 4. The higher the SIL number, the lower the PFD for the safety system, indicating a better system performance. Also, it has been found that the higher the SIL number, the higher the cost and complexity of the system will be. SIL is applicable and calculated for an entire SIF system, but not on individual products or components. As described earlier, each SIF is assigned an SIL. The reliability and availability of SIF due to SIL are achieved by design, design installation, and testing. SIL is also dependent on architectural constraints.

4.1.1 SIL CATEGORIES

The following points on SIL are worth noting [4]:

1. **SIL 0/none:** lowest risk;
2. **SIL 1:** 95% of the SIFs;
3. **SIL 2:** 5% of SIFs;
4. **SIL 3:** <1% (mainly for offshore platforms/ nuclear);
5. **SIL 4:** highest risk (nuclear industry).

From Subsection 4.0.0.1, one gets that SIS is meant to prevent, control, or mitigate hazardous events and take the process to a safe state when predetermined conditions are violated.

4.1.2 SIL, PFD, AND AVAILABILITY INTERRELATIONS

The interrelation amongst SIL, PFDs, and availability has been given in Tables AV/4.1.0-1 and AV/4.1.0-2.

4.2.0 SIL Determination Techniques

Manufacturers specify SIL/PFD for its equipment. However when these are implemented in a loop it is necessary to determine SIL for the loop. SIL is determined for the entire loop pertinent to one SIF with the SIL/PFD value specified by the manufacturer. Of the many plant hazard analysis (PHA) techniques, plant hazard analysis (quantitative) techniques such as fault tree, event tree, layer of protection analysis (LOPA) can be used to determine SIL. Detailed hazard analysis methods have been detailed out in Ref. [1]. However, prior to that let us look into the major steps involved to determine the SIL for SIF:

- To carry out the PHA of the process by selecting any suitable method of PHA;
- Reveal the study result with cause, consequence, recommended safety, etc.;
- Identification of hazards and existing safeguards;
- Identification and initiating cause and development of hazardous scenario;
- Quantification efforts for hazard frequency and safeguard reliability.

The following techniques can be utilized to determine SIL of SIF:

1. Direct by calculation;
2. SIL determination by fault tree;
3. SIL determination by the safety matrix method;
4. SIL determination by risk graph;
5. LOPA for SIL determination;
6. SIL determination by comparison.

Each of these methods are elaborate and in order to limit the volume of the book it is not possible to describe them in appendix.

TABLE AV/4.1.0-1 SIL and PFD (Ref: IEC 61508)

Safety Integrated Level (SIL)	Mode of Operation (PFD_{avg})	
	On Demand	Continuous
4	$\geq 10^{-5}$ to $< 10^{-4}$	$\geq 10^{-9}$ to $< 10^{-8}$
3	$\geq 10^{-4}$ to $< 10^{-3}$	$\geq 10^{-8}$ to $< 10^{-7}$
2	$\geq 10^{-3}$ to $< 10^{-2}$	$\geq 10^{-7}$ to $< 10^{-6}$
1	$\geq 10^{-2}$ to $< 10^{-1}$	$\geq 10^{-6}$ to $< 10^{-5}$

TABLE AV/4.1.0-2 Interrelationship Amongst SIL, PFD_{avg}, Availability, and Consequence

SIL	PFD_{avg}	Availability (%)	Consequence (Fatality)
SIL1	10^{-2} to 10^{-1}	90–<99	Minor on-site injury
SIL2	10^{-3} to 10^{-2}	99–<99.9	Major on-site injury or may be fatality
SIL3	10^{-4} to 10^{-3}	99.9	Multiple on-site fatalities
SIL4	10^{-5} to 10^{-4}	>99.99	Fatality in community

SIL1, lowest SIL; *SIL4*, highest defined SIL.

Interested readers may refer Chapters VII & VIII of Ref. [1] for SIL and SIL determination methods.The reader should note that flow meters and/or metering pumps in safety applications are specified with suitable SIL value attached, e.g., *Functional safety—SIL2 or SIL3 XXX type flow meter. It is worth noting that while specifying the meter they also specify the architecture like (1oo1* or 1oo2*, etc.)*. This means that specified SIL (SIL 2/3) certification is available for the meter for working in that architecture also. From here it transpires that SIL is dependent on the architecture or configuration (which modifies reliability*), e.g., *Siemens's SITRANS FC 430 compact C23 has SIL certification of SIL 2/3 and is suitable for both 1oo1 and/or 1oo2 architecture**. With this, the discussion on SIL comes to an end. Interested readers may refer to Ref. [1]* for details.

Let us now look into the enclosure details necessary for various flow meters so that these can be used in hazardous applications.

LIST OF ABBREVIATIONS

BPCS Basic process/plant control system
HFT Hardware failure tolerance
PFD Probability of failure on demand
SFF Safe failure fraction
SIF Safety instrumented function
SIL Safety integration level
SIS Safety instrumented system

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[2] A. Richardson, A Culture of Safety, Flow control, October 2011. https://www.flowcontrolnetwork.com/a-culture-of-safety/.

[3] Controlling Risks Safety Lifecycle, USPAS, January 2012. http://uspas.fnal.gov/materials/12UTA/06_lifecycle.pdf.

[4] J.L. Bergstrom, Safety Instrumented Systems (SIS) and Safety Life Cycle, Process Engineering Associates, LLC, September 2009.

APPENDIX VI

ENCLOSURE ELECTRICAL PROTECTION

*This appendix has mainly been developed from the book entitled "**Plant Hazard Analysis and Safety Instrumentation Systems**" by Swapan Basu (AP—Elsevier & IChemE), which deals with detailed analysis of plant hazards analysis and suggested safety instrumentation as a safe guard against that. The author thanks Elsevier for the book. Interested readers may go through the same for detailed discussions on the issues.*

1.0.0 GENERAL DISCUSSIONS

Of the various products and intermediate products in industrial or process industries there are many which can form explosive mixtures with other products or with the oxygen in the air. Flammable gases, vapors, mists, dusts, and fibers escape during production, processing, transportation, and storage of flammable substances in many industries. These flammable gases, vapors, mists, and dusts form an explosive atmosphere with oxygen or air. When this explosive atmosphere comes into contact with energy, such as ignitions, sparks, hot surfaces, etc., explosions may take place and cause severe damage/harm to people, property, and the environment. It is necessary to see that measurement and control equipment that comes into contact with such mixtures does not cause an explosion, but can operate effectively. So, it is better to understand how such explosion can occur! In this connection Explosion triangle will be nice to conceive the same.

1.0.1 EXPLOSION TRIANGLE

Similar to a fire triangle, there is also a triangular requirement for flammable materials that cause an explosion, as shown in Fig. AVI/1.0.0-1.

From the above figure it is clear that there must be three things available in their requisite quantity for an explosion to take place.

- A sufficient degree of dispersion (degree of scattering) for mist or dust requires particle sizes between 0.1 and 0.001 mm. For gases this degree is provided by nature [1].
- Explosion can only happen when the concentration of a flammable substance in *air/Oxygen* lies between the minimum and maximum values for the material required for explosion.
- The requisite quantity of *air/Oxygen* is present.
- An ignition source with sufficient energy is present to initiate the explosion.

In *workplaces*, hazardous areas can develop wherever the first and third preconditions for an explosion are fulfilled. In a workplace there has to be air and oxygen. Typical hazardous areas are created by flammable gases and vapors from

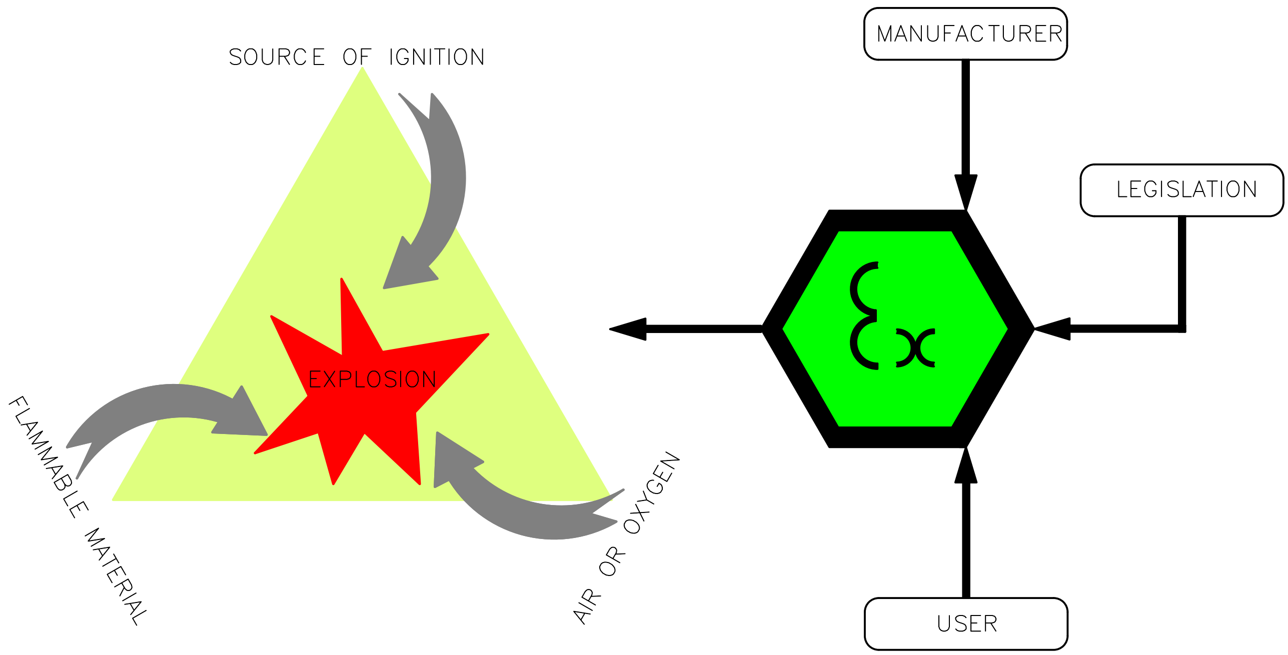


FIGURE AVI/1.0.0-1 Explosion and protection.

chemical/petrochemical factories, refineries, offshore plants, tank facilities, loading areas for flammable materials, and/or boiler areas of natural gas-based power plants, and also dusts in milling plants, pulverizers in power plants, etc. This means that emphasis will be on flammable materials and sources of energy for ignition because oxygen cannot be dispensed with. According to the Occupational Safety and Health Administration (OSHA):

"Flash point is the minimum temperature at which a liquid gives off vapor within a test vessel in sufficient concentration to form an ignitable mixture with air near the surface of the liquid. The flash point is normally an indication of susceptibility to ignition." Also as per OSHA, combustible liquids are defined as "any liquid having a flash point at or above 100F (37.8°C)." Flammable liquids are classified into different groups with different names such as flammable, combustible, and extremely flammable by OSHA, NFPA, and ANSI.

1.0.2 RANGE OF EXPLOSION

As mentioned above, flammable materials must be present with a concentration of a flammable substance in *air/Oxygen* that lies between the minimum and maximum values for the material required for explosion. Therefore, the lower explosive limit (LEL) and upper explosive limit (UEL) are two extreme limits and play an important role in determining the cause of an explosion. The role of the concentration of flammable material in an explosion is well depicted in Fig. AVI/1.0.0-2.

It is clear from the above figure *(shows both extreme conditions for both flammable materials and air/Oxygen)* that when the concentration of flammable material is too high or too low (beyond the limits), then no explosion will occur on account of lack of oxygen and lack of flammable materials, respectively. Instead, there is just a steady-state combustion reaction or none at all.

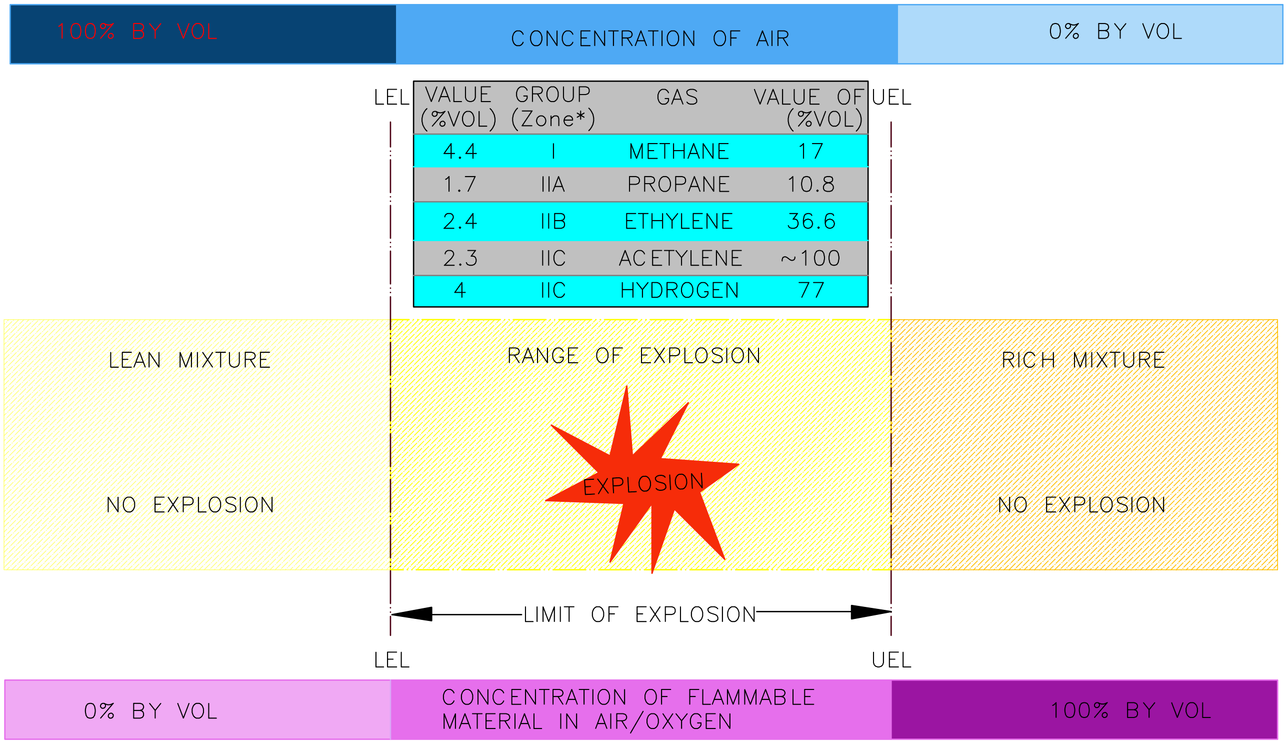


FIGURE AVI/1.0.0-2 Range and limit of explosion.

1.0.3 COMPONENTS FOR EXPLOSION

Let us now look into the components necessary for an explosion to happen. There are three components necessary and these are described here:

1. **Flammable substances:**
   - *Flammable gases/vapors:* A flammable gas may be in the form of an element, such as H2, or often compounds of carbon and hydrogen (hydrocarbon, e.g., natural gas), or oxidation reaction of carbon (in complete combustion in furnace), which can react with oxygen with very little additional energy. A vapor is the proportion of a liquid that has evaporated into the surrounding air as a result of the vapor pressure above the surface of the liquid, for example, around a jet or droplets of the liquid. When spraying a flammable liquid, a mist (highly inflammable) can form consisting of very small droplets with a very large overall surface area.
   - *Flammable liquids:* Flammable liquids are mostly hydrocarbon compounds, e.g., petroleum spirit. Many other liquids can form such an atmosphere near the surface at increased temperatures. The flammable liquids with a flash point at room temperature or below are more dangerous than their counterparts with a high flash point. Fine mists formed from a flammable liquid are also dangerous.
   - *Solid particles:* For solids, particle fineness, surface area, and chemical properties are important. Generally, solids require more energy than do gases and vapors to activate the explosion in air. However, once combustion starts, the energy released by the reaction can produce high temperatures and pressures. Dust reacts very differently, depending on whether it is in a deposited layer or in a suspended dust cloud [2]. Normally, smoldering first starts in dust layers on hot surfaces (secondary combustion in a hot furnace is an example), whereas in a dust cloud when ignited locally

or through contact with a hot surface, it can explode immediately.

2. **Air/oxygen:** The stoichiometric ratio is responsible for determining the quantity of oxygen necessary to react with available flammable materials. Naturally, when the quantity of the flammable material and the available atmospheric oxygen are near to the stoichiometric ratio, the reaction will be near completion and cause an explosion with an increase in temperature and pressure. The explosion can be violent. When the quantity of flammable material is too small, combustion cannot spread and may cease. The situation is similar when the quantity of flammable material is too large, because the lack of the required quantity of O_2 means that the reaction cannot proceed further. This is indicated through the LEL and UEL in Fig. AVI/1.0.0-2. It may be possible to dilute flammable materials in excess air, but in view of the work force, it is not possible to create a dearth of oxygen. This is only applicable inside equipment.
3. **Sources of ignition:** There are several sources from where energies may come to ignite an explosive atmosphere. In this connection EN 1127-1:2007 (especially, clauses 4.3 and 5.3.1) may be referenced. The basic sources are listed below. The reference indicated in parentheses refers to the clause in EN 1127-1:2007.
   - *Hot surface (5.3.2):* Heated surface (e.g., heater, metal cuttings), dust layers, etc. can cause ignition. It is dependent on the type and concentration of the particular substance in the explosive mixture.
   - *Flames and hot gases including hot particles (5.3.3):* Even very small flames are among the most effective sources of ignition. Flames, their hot reaction products, or otherwise highly heated gases can ignite an explosive atmosphere.
   - *Mechanically generated sparks (5.3.4):* These can be generated as a result of friction, impact, or abrasion processes, for example, in grinding particles are hot because of the energy required for separation.
   - *Electrical apparatus (5.3.5):* These are always considered as a sufficient source of ignition, i.e., opening and closing of electrical circuit, loose connection, and stray current.
   - *Stray electric current/cathodic corrosion protection (5.3.6):* Stray currents can flow in electrically conductive systems or parts of systems, i.e., return currents, short circuit, magnetic induction, etc. to name a few.
   - *Static electricity (5.3.7):* The discharge of charged, insulated conductive parts can easily lead to incendive sparks, i.e., the stored energy can be released in the form of sparks (as an ignition source).
   - *Lightning (5.3.8):* When lightning strikes in an explosive atmosphere, ignition will always occur. Also, there can be ignition of an explosive mixture because of the high temperature caused by lightning.
   - *Radiofrequency electromagnetic waves from* 10^4 *to* 3×10^{12} *Hz (5.3.9):* Systems that generate and use radiofrequency electrical energy, such as radio transmitters or radiofrequency generators for heating, drying, hardening, welding, and cutting, emit radiofrequency waves.
   - *Radiofrequency waves from* 10^{11} *to* 3×10^{15} *Hz (5.3.10):* Radiation in this spectral range can (especially when focused) become a source of ignition through absorption by explosive atmospheres or solid surfaces.
   - *Ionizing radiation (5.3.11):* This is generated, for example, by X-ray tubes, and radioactive substances can ignite explosive atmospheres (especially explosive atmospheres with dust particles) as a result of energy absorption.
   - *Ultrasonic (5.3.12):* In the use of ultrasonic sound waves, a large proportion of the energy emitted by the electro-acoustic transducer is absorbed by solid or liquid substances.
   - Two other types are adiabatic compression and shock waves (5.3.13) and exothermic reactions (5.3.14), including self-ignition of dusts.

1.1.0 Electrical Area Classification

Based on the chances of explosion, normally plant or work place areas are classified. This area classification is actually a hazardous area classification. Since the main focus is on electronic instrumentation systems, it has been designated as electrical area classification (EAC) to indicate that attention will be given to the selection of instruments and associated enclosures, etc. In this section brief discussions shall be presented on this. These area classifications have been made in two ways:

Class and division method (North America);
Zone division method (Europe and other parts of the world) as indicated Fig. AVI/1.1.0-1.

However, with the introduction of IEC standards this is somewhat similar to the second type and is mainly followed globally; even the NEC has included zone divisions. Though this area classification covers electrical equipment, e.g., motors, our focus will be on instrumentation only. Major issues of concern include but are not limited to the following:

- Type of hazards;
- Type of flammable material present;
- Flammable material properties and concentration;
- Likelihood of the presence of flammable material;

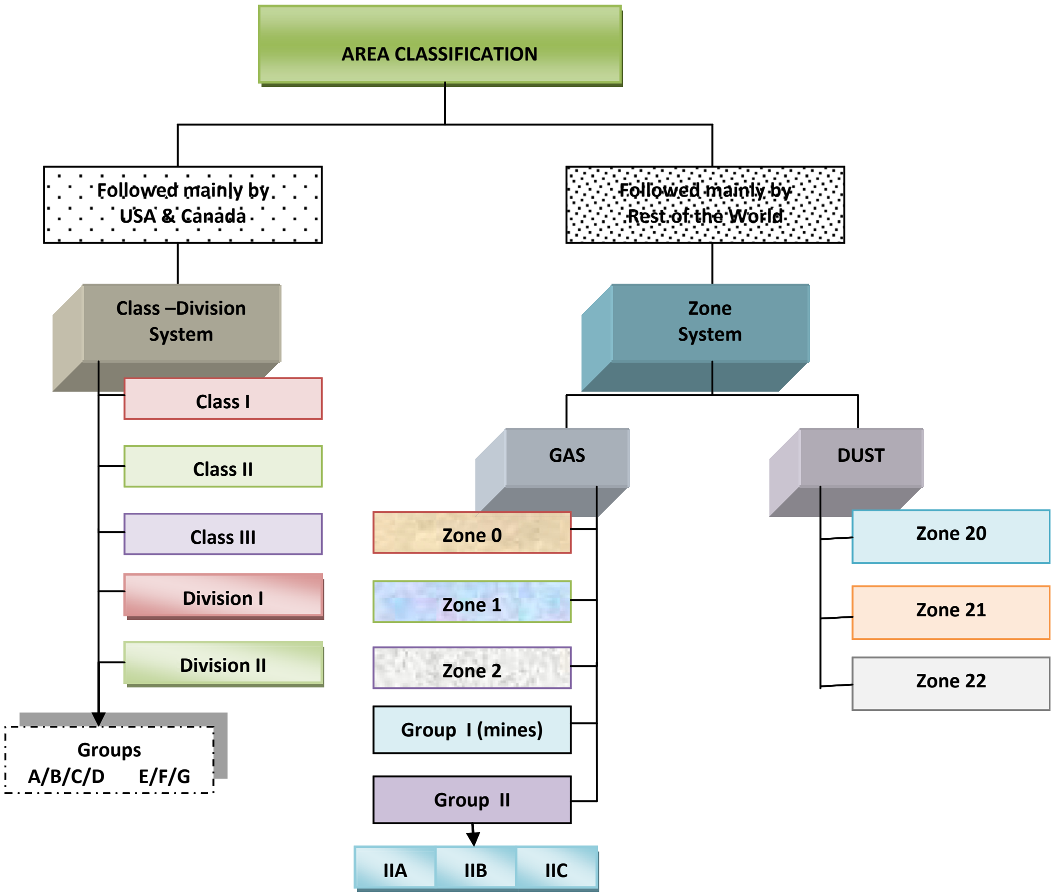


FIGURE AVI/1.1.0-1 Hazardous area classification chart.

- Flammable materials present as normal or because of malfunction;
- Area/location temperature;
- Auto-ignition temperature of flammable material;
- Sources and types of ignition energy.

Here, in order to limit the discussions, detailed discussions will not be presented, only the applicable important charts have been presented. Interested readers may refer to Chapter X of Reference [3], where a detailed account of these have been given.

1.1.1 CLASS DIVISION CLASSIFICATIONS

1. **Class:** In this division classes have been chosen based on the flammable material present. This is detailed in Table AVI/1.1.1-1.
2. **Division:** Divisions have been created based on their likelihood of presence. This has been elaborated in Table AVI/1.1.1-2.
3. **Group:** Hazardous materials in the surrounding areas are grouped. Their grouping and applicability are given in Table AVI/1.1.1-3

TABLE AV/1.1.1-1 Class—General Nature of Hazardous Materials

Class	Area
I	Area/location in which flammable gases or vapors[1] may (or may not[2]) be present in sufficient quantities to produce explosive or ignitable mixtures. *1: Important is gas/vapor* *2: May not: qualifies sufficient to indicate chances of explosion.*
II	Area/location in which combustible or conductive dusts[1] (in suspension intermittently, or periodic) may (or may not[2]) be present in sufficient quantities to produce explosive or ignitable mixtures. *1: Important is combustible or conductive dusts* *2: May not: qualifies sufficient to indicate chances of explosion.*
III	Area/location in which ignitable fibers[1], not likely to be in suspension, may (or may not[2]) be present, in sufficient quantities to produce explosive or ignitable mixtures. *For this class grouping does not have any relevance.* *1: Examples: Wood chips, cotton, nylon, etc.* *2: May not: qualifies sufficient to indicate chances of explosion.*

TABLE AVI/1.1.1-2 Division—Likelihood of Hazardous Material Present

Division	Presence of Hazardous Materials
I	The substance referred to by class, is present *continuously, intermittently,* or *periodically* or present *due to normal operation*, and has high probability of producing explosive or ignitable mixtures
II	The substance referred to by class is present only in abnormal conditions (such as a container failure or system breakdown) or for a short duration and has low probability of producing explosive or ignitable mixtures

TABLE AVI/1.1.1-3 Grouping of Hazardous Materials

Group	Hazardous Materials	Applicable
A	Acetylene	Gases/vapors Class I
B	Hydrogen, fuel, and combustible process gases containing more than 30% hydrogen by volume or gases of equivalent hazard such as butadiene, ethylene, oxide, propylene oxide, and acrolein	
C	Cyclopropane, CO, ether, hydrogen sulfide, morphline, ethyl ether, and ethylene or gases of equivalent hazard	
D	Acetone, ammonia, benzene, butane, cyclopropane, ethanol, gasoline, hexane, methanol, methane, vinyl chloride, natural gas, naphtha, propane or gases of equivalent hazard	
E	Combustible metal dusts: aluminum, magnesium, and their commercial alloys or other combustible dusts whose particle size, abrasiveness, and conductivity present similar hazards in connection with electrical equipment	Dusts & flying Class II
F	Carbonaceous dusts, carbon black, coal black, charcoal, coal/coke dusts (>8% total entrapped volatiles)	
G	Dusts not included in E and F such as flour dust, grain dust, flour, starch, sugar, wood, plastic, and chemicals	

1.1.2 ZONE SYSTEM—ATEX DIRECTIVE

[The word ATEX has a French origin. It is the English equivalent of **AT**mosphères **EX**plosibles.]

Zone classification has been presented in Table AVI/1.1.2-1.

The "Directive on Equipment and Protective Systems Intended for use in Potentially Explosive Atmospheres" (94/9/EC) came into force on March 1, 1996. The EU and some other countries follow this directive popularly known as ATEX 95. This should not be ***confused*** with work place area classification, which is covered by a separate directive known as ATEX 137.

The zone system group and category classification has been illustrated with the help of Table AVI/1.1.2-2 presented after the discussions on groups and categories. In this connection product acceptability in ATEX is very important and the associated standard (also explained in Reference [3]) may be referenced.

1. **Group I:** This is meant for ***mining*** applications with two categories under it.
   - *Category M1:* Equipment in this category should remain functional in an explosive atmosphere present (in mining)—required protection level "*Very High.*"
   - *Category M2:* Equipment requires to be de-energized in an explosive atmosphere present (in mining)—required protection level "*High.*"
2. **Group II:** This is meant for equipment to be used in other (than **mine** use) locations endangered by potential explosive atmosphere. Here both gas and dust systems are considered and in markings these are distinguished by "**G**" or "**D**" to indicate whether meant for gas or dust, respectively. This group has following categories. Gas group II has further subdivisions as *IIA* (propane or equivalent), *IIB* (ethylene or equivalent) and *IIC* (H2, acetylene or equivalent).

TABLE AVI/1.1.2-1 Zone Classification Table (Gas and Dust)

Material	Zone	Explanation
Gas	0	A location in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapor, or mist is present *continuously, or long periods or frequently*
Gas	1	A location in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapor, or mist is *likely* to occur in normal operation *occasionally*
Gas	2	A location in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapor, or mist is not *likely* to occur in normal operation but, if it does occur, will persist for a *short* period only
Dust	20	A place in which an explosive atmosphere in the form of a cloud of combustible dust in air is present *continuously or long period or frequently*
Dust	21	A place in which an explosive atmosphere in the form of a cloud of combustible dust in air is *likely* to occur in normal operation *occasionally*
Dust	22	A place in which an explosive atmosphere in the form of a cloud of combustible dust in air is not *likely* to occur in normal operation but, if it does occur, will persist for a *short* period only

TABLE AVI/1.1.2-2 Area Classification for Equipment in Explosive Atmosphere (ATEX95)

Group/ Category	Group I: Equipment in Mines Below or Above Ground	Group II: Equipment in Other Locations, Endangered by Explosive Atmosphere
Category 1	Category M1 (Cat M1)	Category 1 (Cat 1)
Category 2	Category M2 (Cat M2)	Category 2 (Cat 2)
Category 3	Not applicable	Category 3 (Cat 3)

- *Category 1:* Equipment in this category is intended for use in areas in which explosive atmospheres caused by mixtures of air and gases/vapors/mists or by air/dust mixtures are present *continuously*, for long periods, or frequently. Equipment or protective systems need to guarantee a "*very high level*" of protection and are duly certified by notified body (e.g., CESI/IMQ/TUV ATEX site may be visited).
- *Category 2:* Equipment in this category is intended for use in areas in which explosive atmospheres caused by mixtures of air and gases/vapors/mists or by air/dust mixtures are likely to occur. Equipment or protective systems need to guarantee a "*high level*" of protection with due certification from the notified body.
- *Category 3:* Equipment in this category is intended for use in areas in which explosive atmospheres caused by gases, vapors, mists, or air/dust mixtures are unlikely to occur or, if they do occur, are likely to do so only infrequently and for a short period only. Equipment or protective systems that

guarantee "a normal level" of protection. Self-certification (internal control) is allowed in this category if the manufacturer has sufficient testing facilities.

1.2.0 Temperature Class

As discussed in the clause in Subsection 1.0.3.3, depending on factors like size, shape, type and surface quality, gas concentration, flammable materials, especially gases, may ignite when coming into contact with a hot surface. In all standards (refer to IEC 60079-20-1), gases and vapors are divided into temperature classes. Approved equipment receives a temperature code indicating the maximum surface temperature **limit** of the equipment. This means that surface temperatures in explosion-protected equipment and other technological objects are designed in such a way that ignition by the surface is not possible [4]. Table AVI/1.2.0-1 presents the ignition temperature as per NEFA 497 art 500 and ATEX.

Under the main Section 1.0.0 we have seen how explosion can take place and what the electrical area classification types are. It is now time to go into the protection types suggested in different standards. These shall be discussed in the next section.

2.0.0 PROTECTION: PHILOSOPHY AND SELECTION

In this section the philosophy behind protection selections will be discussed. The discussion start with a class division as in NFPA (National Fire Protection Association USA).

2.1.0 NFPA Method of Protection

National Fire Protection Association (NFPA) standard NFPA 70 (NEC) article 500 (500-7)

TABLE AVI/1.2.0-1 Surface Temperature Division and Electrical Apparatus Temperature Limit

Temperature Code	Ignition Temp[a]. in °C (°F)	Ignition Temp[b] Range in °C	Permissible Temperature Electrical Apparatus in °C[c]
T1	450 (842)	>450	450
T2	300 (572)	>300 to ≤450	300
T2A	280 (536)		
T2B	260 (500)		
T2C	230 (446)		
T2D	215 (419)		
T3	200 (392)	>200 to ≤300	200
T3A	180 (356)		
T3B	165 (329)		
T3C	160 (320)		
T4	135 (275)	>135 to ≤200	135
T4A	120 (248)		
T5	100 (212)	>100 to ≤135	100
T6	85 (185)	>85 to ≤100	85

[a]*As per NFPA 497 art 500.*
[b]*As per ATEX.*
[c]*Based on ATEX data.*

TABLE AVI/2.1.0-1 Protection Concepts Class Division System

Method	Class	Division	Remarks
Explosion proof	I	1, 2	
Dust ignition proof	II	1, 2	
Dust tight	II	2	
	III	1, 2	
Purged and pressurized	—	—	Classified area for which it is identified
Intrinsic safe	I	1, 2	
	II	1, 2	
	III	1, 2	
Nonincendive circuit	I	2	
	II	2	
	III	1, 2	
Nonincendive equipment		As above	
Nonincendive component		As above	
Oil immersion	I	2	
Hermetically sealed	I	2	
	II	2	
	III	1, 2	
Combustible gas detector		Means of protection in industry with restricted public access elec.	
Inadequate ventilation		Classified class 1 division1 for inadequate ventilation. Elec. Apparatus Class I division 1	

2012, specifies various explosion equipment for electrical apparatus as listed in Table AVI/2.1.0-1. In the following table, sequential details as per NFPA70 art 500-7 (A through L) have been presented.

2.2.0 ATEX Method of Protection

ATEX: The ATEX concept of protection has been elaborated in Table AVI/2.2.0-1. This may be compared with Table AVI/2.3.0-1 for IEC.

TABLE AVI/2.2.0-1 ATEX Protection Concept

Concept	Code	Zone	Category	Principle of Protection
Increased safety	Ex e	1, 2	2, 3	No arc, spark, or hot surface
Nonsparking	Ex nA	2	3	No arc, spark, or hot surface
Flame proof	Ex d	1, 2	2, 3	Contain the explosion. Quench the flame
Enclosed break	Ex nW	2	3	

Continued

TABLE AVI/2.2.0-1 ATEX Protection Concept—cont'd

Concept	Code	Zone	Category	Principle of Protection
Quartz/sand-filled	Ex q	1, 2	2, 3	Contain the explosion. Quench the flame
Intrinsic safety	Ex ia	0, 1, 2	1, 2, 3	Limit the energy of spark and limit the temperature
Intrinsic safety	Ex ib	1, 2	2, 3	
Energy limitation	Ex nL	2	3	
Pressurize	Ex p	1, 2	2, 3	Keep the flammable gas from hot surface and ignition capable equipment
Simplified pressurization	Ex nP	2	3	
Encapsulation	Ex m	1, 2	2, 3	Same as above
Oil immersion	Ex o	1, 2	2, 3	Same as above
Restricted breathing	Ex nR	2	3	
Special	Ex s	0, 1, 2	1, 2, 3	Any proven method

TABLE AVI/2.3.0-1 IEC—EPL Protection Techniques (Gas)

Method	Code Ex	EPL	Zone	IEC[a]	Principles of Protection
Increased safety	e	Gb	1, 2	7	No Arc, spark or hot surface. IP54 or better
Type n (nonsparking)	nA	Gc	2	15	
Flame proof	d	Gb	1, 2	1	Contain the explosion. Quench the flame
Type n (enclosed break)	nC	Gc	2	15	
Quartz/sand filled	q	Gb	1, 2	5	Quench the flame
Intrinsic safety	ia	Ga	0, 1, 2	11	Limit energy of spark and surface temperature
Intrinsic safety	ib	Gb	1, 2	11	
Intrinsic safety	ic	Gc	1, 2	2	
Type n (energy limiting)	nL	Gc	2	15	
Pressurized	p, px	Gb	1, 2	2	Keep the flame gas out
	py	Gb	1, 2	2	
	pz	Gc	2	2	
Type n (hermetic sealing)	nC	Gc	2	15	
Type n (restricted breathing)	nR	Gc	2	15	
Type n (simple pressurized)	nZ	Gc	2	15	
Encapsulation	ma	Ga	0, 1, 2	18	Keep the flame gas out
Encapsulation	mb	Gb	1, 2	18	
Oil immersion	o	Gb	1, 2	6	Keep the flame gas out

[a] *IEC column: IEC 60079-Part, e.g., 7 in IEC column = IEC 60079-7.*

TABLE AVI/2.3.0-2 IEC—EPL Protection Techniques (Dust)

Method	Code Ex	EPL	Zone	IEC[a]	Principles of Protection
Enclosure	t	Da, Db, Dc	20	31	Standard protection for dust-tight enclosure
Intrinsic safety	i	Da, Db, Dc	21	11	Same as above, some relaxation for intrinsic circuit
Encapsulation	m	Da, Db, Dc	22	18	Protection by encapsulation of incendive part
Pressurized	p	Db, Dc	21, 22	2	Protection by pressurization of enclosure

[a] *IEC column: IEC 60079-Part, e.g., 7 in IEC column = IEC 60079-7.*

2.3.0 IEC Method of Protection

In the IEC standard, the protection of equipment is represented by the equipment protection level (EPL). As per the IEC standard there are different tables for gas and dust. In IEC, EPLs for gas and dust are distinguished by G and D, respectively. Similar to ATEX there are different categories. EPL for categories (1, 2, 3 of ATEX) are a, b, and c.

- *IEC—Gas:* EPL for gas with applicable zone and protection principles elaborated in Table AVI/2.3.0-1 to help in the selection process.
- *IEC—Dust:* EPL for dust with applicable zone and protection principles elaborated in Table AVI/2.3.0-2, to help in the selection process.

3.0.0 EXPLOSION PROTECTION PRINCIPLE ENCLOSURE CLASS AND INTRINSIC SAFETY

In this section explosion protection and various enclosure classes used to prevent explosion have been covered.

3.1.0 Explosion Protection Principles

The main aim of explosion protection in instrumentation is to prevent ignition sources or the coming together of such sources with potentially explosive atmospheres. Protection principles focus on the ways and means to exclude equipment and components as ignition sources. Ignition sources are prevented in explosion-protected equipment by selecting appropriate materials and by constructive measures. Another way is to limit the energy level from the equipment to prevent an explosion. All these must be verified and confirmed by the appropriate tests. Generally, four protection principles, as detailed in Fig. AVI/3.0.0-1, are used to prevent explosion to any equipment by protecting it and limiting its energy, so that it cannot become a source of ignition. In all of four the protection principles depicted in Fig. AVI/3.0.0-1, it is necessary to ensure that an explosive atmosphere must not be able to reach nonpermitted temperatures with respect to the ignition temperature of substances present in the surrounding atmosphere.

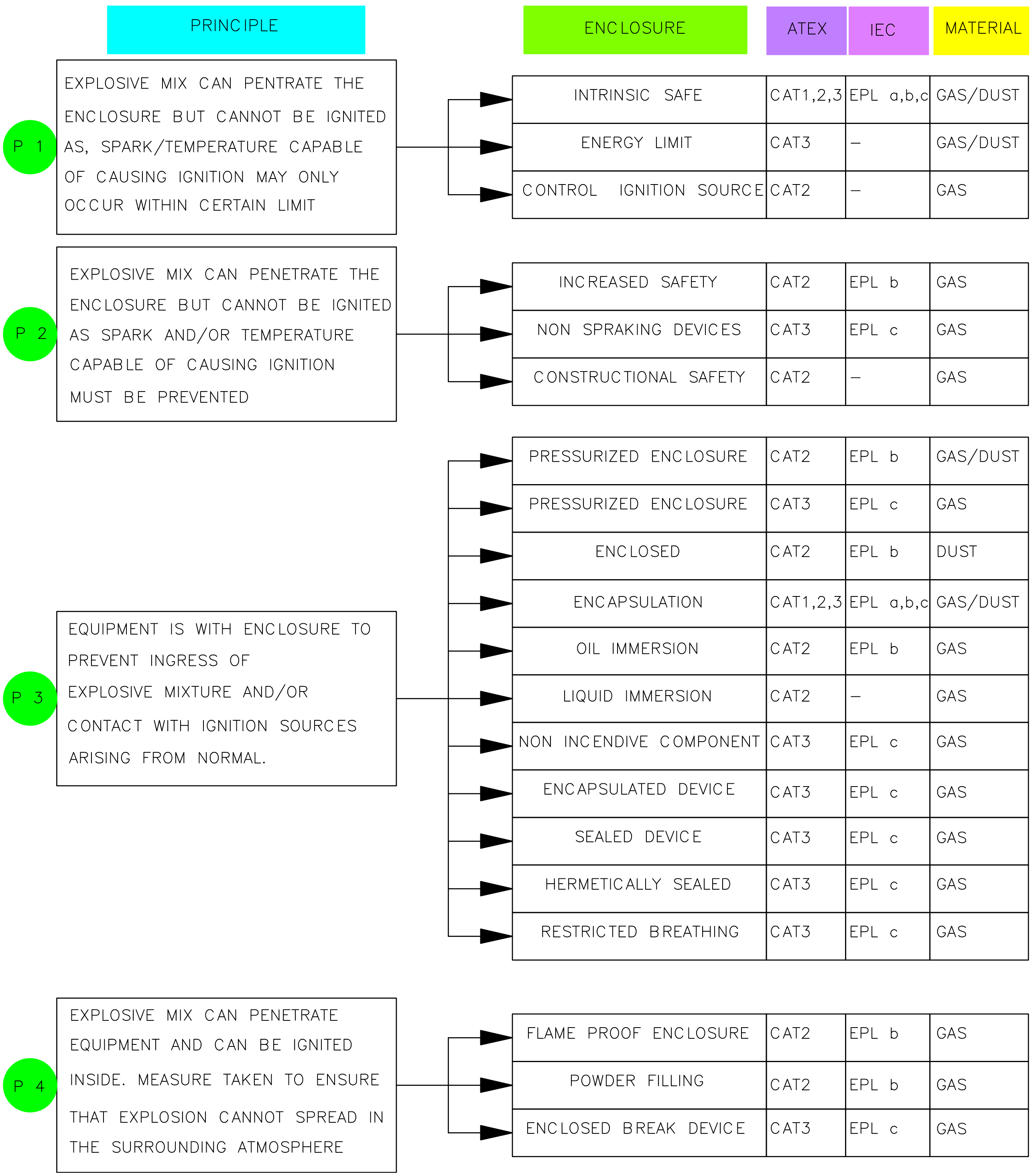


FIGURE AVI/3.0.0-1 Explosion protection principles.

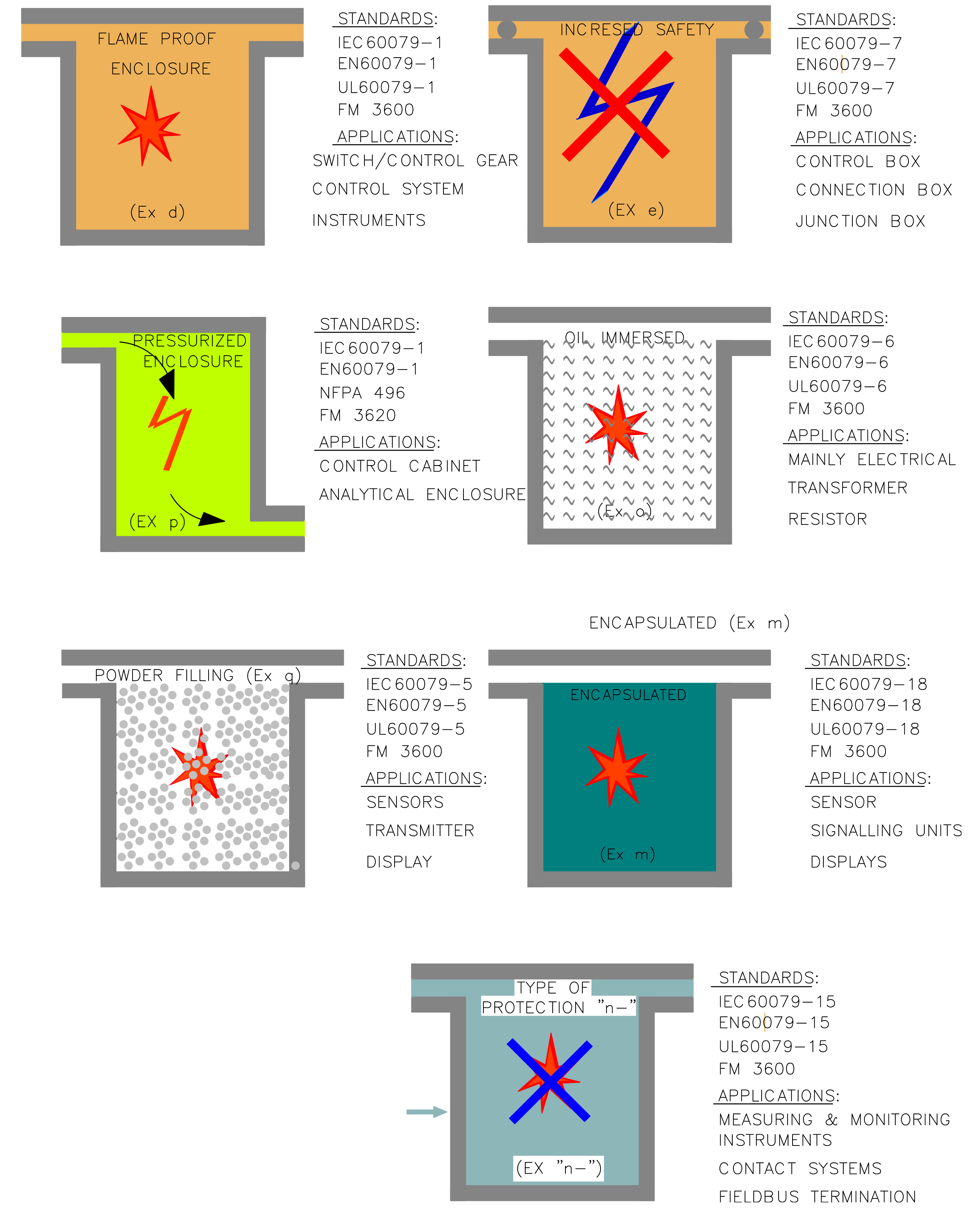


FIGURE AVI/3.0.0-2 Enclosure classes and types. *nA*, nonsparking apparatus; *nC*, sparking apparatus in which contacts are protected; *nL*, energy limited; *nR*, restricted breathing; *nZ*, purged and pressurized.

3.2.0 Enclosure Classes

From the above discussions, it is clear that there will be several kinds of enclosure classes used in process and industrial plants as protection against explosion. Fig. AVI/3.0.0-2 shows various enclosures with their characteristics and application areas and associated standards.

Fig. AVI/3.0.0-2 is self-explanatory; however, for a detail account on this any standard book on enclosure class or Chapter X of Reference [3] may be referenced. Apart from various enclosures, there is another vital kind of explosion protection. This is intrinsic safety protection.

3.3.0 Intrinsic Safety (IS)

IS in instrumentation and controls for hazardous areas is very important and a common means of explosion protection. As per IEC 60079-11, IS can be conceived as a "type of protection based on the restriction of electrical energy within apparatus and of interconnecting wiring exposed to the potentially explosive atmosphere to a level below that which can cause ignition by either sparking or heating effects." The equipment installed in the hazardous area are made intrinsically safe by using intrinsic safe circuit placed in safe region. Intrinsic safe circuits limit the energy flow to field equipment to prevent from explosion. A circuit is intrinsically safe when sparks or thermal effects cannot occur under defined test conditions (which include normal operation and certain malfunctions), which could ignite a particular explosive atmosphere. The categories of intrinsic safety and fault tolerance level with use in several standards have been elaborated in Table AVI/3.0.0-1.

Normally blue cables are used for IS cables to distinguish them from others. For a detailed account on IS clause 3.7 of Chapter X of Reference [3] may be referenced.

4.0.0 INGRESS PROTECTION

As per IEC 60529 the degrees of protection provided by enclosures of electrical equipment is protection cover to protect against the following:

Access by persons to hazardous parts inside the enclosure;
Ingress of solid foreign objects;
Harmful effects caused by the ingress of water.

There are mainly two standards for electrical enclosure as ingress protection. These are IEC 60529 and the National Electrical Manufacturer Association (NEMA).

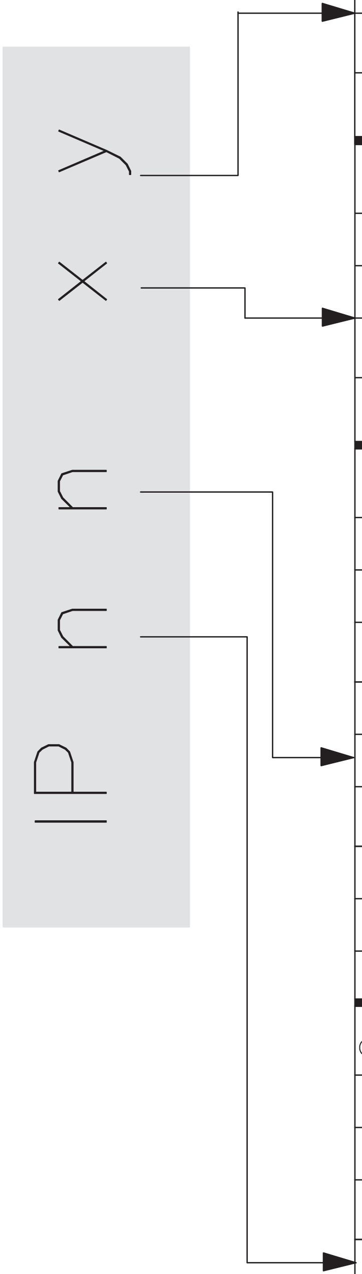
IP rating: IEC ingress protections are represented by **IP *nnXY*** which is decoded in Fig. AVI/4.0.0-1.

IP to NEMA conversion: IP TO NEMA conversion has been depicted in Fig. AVI/4.0.0-2.

NEMA rating: Table AVI/4.0.0-1 gives the details on the NEMA rating for electrical enclosures.

TABLE AVI/3.0.0-1 Comparison and Usage of IS Categories

IS Level	Fault Tolerance	Factor of Safety	ATEX cat	IEC EPL	Zone
ia	2	1.5	1	0	0
ib	1	1.5	2	1	1
ic	0	1	3	2	2



SUPPLEMENTARY LETTER (OPTIONAL)	SUPPLEMENTARY INFORMATION SPECIFIC TO	CLAUSE NO IEC 60529
H	HIGH VOLTAGE	8
M	MOTION DURING TEST	8
S	STATIONARY IN WATER TEST	8
W	WEATHER CONDITIONS	8

ADDITIONAL LETTER (OPTIONAL)	PROTECTION AGAINST HAZARDOUS PART WITH	CLAUSE NO IEC 60529
A	BACK OF HAND	7
B	FINGER	7
C	TOOL	7
D	WIRE	7

SECOND CHARACTER	PROTECTION AGAINST WATER— HARMFUL EFFECT	CLAUSE NO IEC 60529
0	NO PROTECTION	6
1	VERTICALLY DRIPPING	6
2	DRIPPING AT 15 Degrees	6
3	SPRAYING	6
4	SPLASHING	6
5	JETTING	6
6	POWERFUL JETTING	6
7	TEMPORARY IMMERSION	6
8	CONTINUOUS IMMERSION	6

FIRST CHARACTER	PROTECTION AGAINST SOLID FOREIGN OBJECT	PROTECTION AGAINST PERSON	CLAUSE NO IEC 60529
0	NO PROTECTION	NO PROTECTION	5
1	>= 50 mm DIA	BACK OF HAND	5
2	>= 12.5 mm DIA	TOOL	5
3	>= 2.5 mm DIA	FINGER	5
4	>= 1 mm DIA	WIRE	5
5	DUST PROTECTED	WIRE	5
6	DUST TIGHT	WIRE	5

FIGURE AVI/4.0.0-1 Ingress protection code.

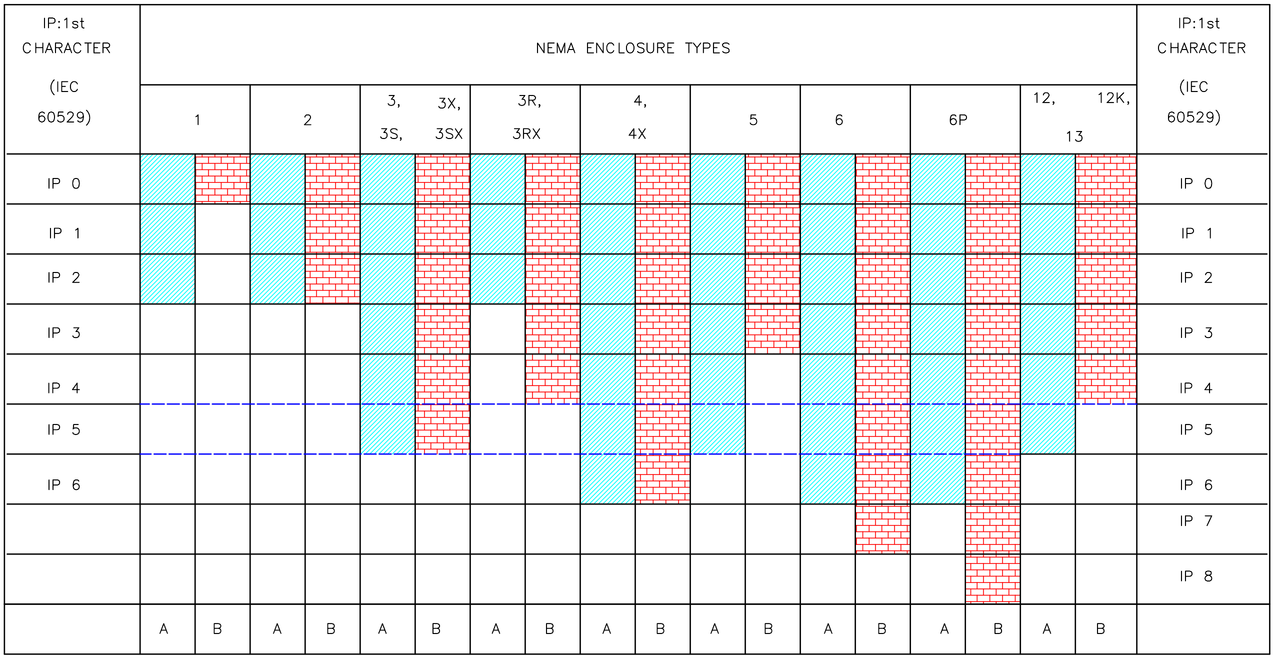


FIGURE AVI/4.0.0-2 Conxversion of IP to NEMA rating. A represents NEMA enclosures types exceeds the requirements for IEC 60529 IP first character shown by cyan hatch, B represents NEMA enclosures types exceeds the requirements for IEC 60529 IP second character shown by red bricks. So, NEMA 4X = IP66 from above chart. Example: conversion of IP 45: first 4 met by 3,3X,3S,3SX/4,4X/5/6/6P/12,1K,13 but for second character 5 only 3,3X,3S,3SX/4,4X/6/6P. Qualify so, they are equivalent to IP45. However many like type 3 exceed IP 45 requirement on account of corrosion gasket aging testing. *Developed based on NEMA 250:2003. Courtesy: NEMA 250:2003.*

TABLE AVI/4.0.0-1 NEMA Enclosure Rating With Interpretation: *(I, Indoor; O, Outdoor—Application) X Indicates Applicability*

Type	I	O	Protection Against: Personnel Access	Protection: (Ingress): Foreign Solid Object	Protection: (Ingress) Water Harmful Effect
1	X		To hazardous part	Falling dirt	
2	X		To hazardous part	Falling dirt	Dripping/light splashing
3	X	X	To hazardous part	Falling dirt, windblown dust	Rain, sleet, snow and external ice formation
3R	X	X	To hazardous part	Falling dirt	Rain, sleet, snow and external ice formation
3S	X	X	To hazardous part	Falling dirt, windblown dust	Rain, sleet, snow. Operable when ice-laden

Continued

TABLE AVI/4.0.0-1 NEMA Enclosure Rating With Interpretation: *(I, Indoor; O, Outdoor—Application) X Indicates Applicability*—cont'd

Type	I	O	Protection Against: Personnel Access	Protection: (Ingress): Foreign Solid Object	Protection: (Ingress) Water Harmful Effect
3X	X	X	To hazardous part	Falling dirt, windblown dust	Rain, sleet, snow and external ice formation and additional corrosion protection
3RX	X	X	To hazardous part	Falling dirt	Rain, sleet, snow and external ice formation and additional corrosion protection
3SX	X	X	To hazardous part	Falling dirt, windblown dust	Rain, sleet, snow and external ice formation and additional level of protection for corrosion. Operable when ice-laden
4	X	X	To hazardous part	Falling dirt, windblown dust	Rain, sleet, snow. Splashing and hose-directed water. Undamaged due to external ice formation on enclosure
4X	X	X	To hazardous part	Windblown dust	Rain, sleet, snow. Splashing and hose-directed water. Additional level of protection for corrosion and undamaged due to external ice formation on enclosure
5	X	–	To hazardous part	Falling dirt and settling airborne dust, lint, fibers, and flying	Dripping and light splashing
6	X	X	To hazardous part	Falling dirt	Hose-directed water, entry of water due to occasional temporary submersion at a limited depth, and undamaged due to external ice formation on enclosure
6P	X	X	To hazardous part	Falling dirt	Hose-directed water, entry of water during prolonged submersion at a limited depth. Additional level of protection for corrosion and undamaged due to external ice formation on enclosure
12/ 12 K[a]	X		To hazardous part	Falling dirt, circulating dust, lint, fibers, flyings	Dripping/light splashing
13	X		To hazardous part	Falling dirt, circulating dust, lint, fibers, flyings	Dripping/light splashing. Also protection against spraying, splashing and seepage of oil and noncorrosive coolants

[a]*12 K with knockout, whereas 12 without knockout.*

5.0.0 ENCLOSURE MARKINGS PROTECTION STANDARDS WITH COMPARISONS

In this section marking of enclosures, various protection types, and their comparisons are presented so that the reader can get to know the pros and cons of each type. The discussions start with enclosure markings.

5.1.0 Enclosure Markings

Various enclosures, especially explosion-proof enclosures, marking on the enclosure are very important. Details of enclosure markings in line with IEC and NEC have been depicted in Fig. AVI/5.0.0-1. Brief details about the same have been presented below.

The typical meaning of each of the markings is indicated also in Fig. AVI/5.0.0-1. Normally, the following information is marked on the plate:

- Manufacturer's name details with model and serial number;
- Conformity mark and ID number;
- Designation for identification;
- *Application zone including:* Group, vapor/dust/mine;
- Categories of approval for specific zones;
- Type(s) of protection the equipment fulfills;
- Explosion group and subgroup;
- Temperature class;
- Ambient specification;
- Test laboratory where the test certificate was issued;
- Standard with versions for certification.

There are some differences in equipment marking types between standard EU/IEC and that of NEC. Detailed equipment markings for both IEC/ATEX (EU) and NEC standards have been elaborated in.

5.2.0 Protection Standards With Comparison

It is needless to say that there are different standards for enclosure protections already discussed. Table AVI/5.0.0-1 depicts various standards and their global geographical areas of use.

Various international enclosure protection standards are compared in Fig. AVI/5.0.0-2.

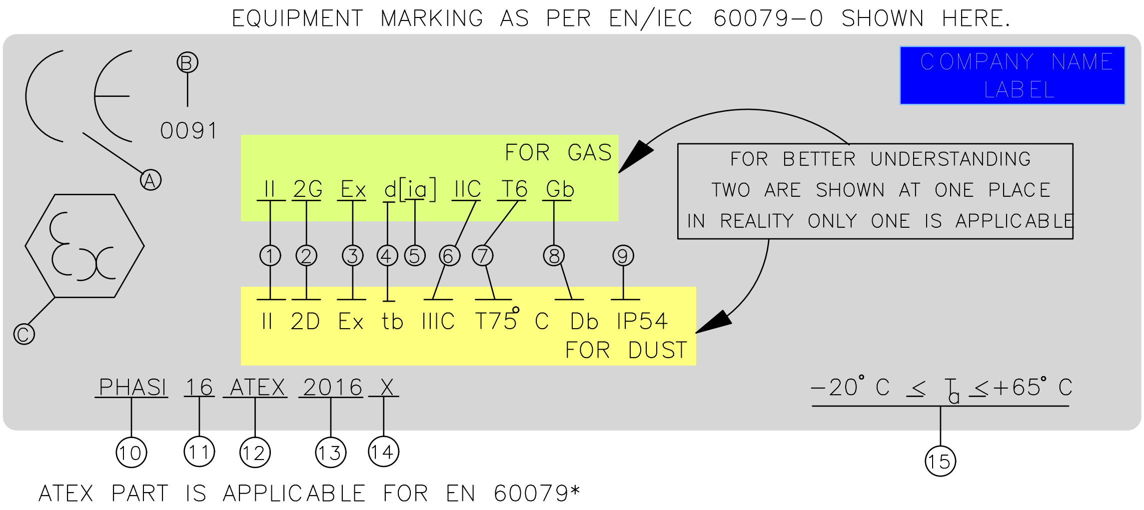
This explosion protection concept is also applicable to fieldbus systems. We conclude the discussions on enclosure electrical protection to address device communication in next appendix (Appendix VII).

TABLE AVI/5.0.0-1 Global Enclosure Protection Standards

Explosive Atmosphere	Geographical Location	Standards	Code
Class I Division 1 and 2	USA	FM3600	—
Class I Division 1 and 2	Canada	CSA C22.2-0	—
Class I Division 1 and 2	USA	ISA 60079-0	AEx
Class I Division 1 and 2	Canada	CSA C22.2-60079-0	Ex
Category 1G/2G/3G	European Union	EN 60079-0	Ex
EPL Ga/Gb/Gc	International IEC[a]	IEC 60079-0	Ex

[a] *Russia and Ukraine follow: GOST Russia/GOST Ukraine Standards; Australia follows IEC but code is IEC Ex. [1].*

(A)



ID	EXPLANATION	REMARKS
A	CONFIRMATORY MARK	
B	ID. NO. OF NOTIFIED BODY	CERTIFYING AUTHORITY; BY QA/PRODUCT TEST
C	Ex MARKING	
1	EQUIPMENT GROUP	NON MINING HERE
2	EQUIPMENT CATEGORY (2*)	*G GAS/D DUST
3	EXPLOSION PROECTION	EN /IEC 60079–
4	PROTECTION TYPE	GAS; FLAME PROOF DUST: BY ENCLOSURE
5	INTRINSIC SAFE OUTPUT	SHOWN ONLY WHERE APPLICABLE.
6	EXPLOSION GROUP	GAS: IIC HERE DUST: IIIC HERE(Cond)

ID	EXPLANATION	REMARKS
7	SURFACE TEMPERATURE CLASS	GAS: CLASS; t6 HERE DUST Surfcae 75 C
8	EQUIPMENT PROTECTION LEVEL	Gb/Db FOR GAS & DUST (Cat:2G/2D–EN*)
9	INGRESS PROTECTION (VIZ.IP54)	FOR DUST APPLICTION
10	CERTIFYING BODY	
11	CERTIFIED – FIRST YEAR	2016 IN THIS CASE.
12	ATEX GENERATION	FOR ATEX ONLY
13	ID DETAILS OF NOTIFIED BODY	ATEX ONLY
14	SPECIAL CONDITION IF ANY	
15	AMBIENT TEMPERATURE	TEMPERATURE RANGE

(B)

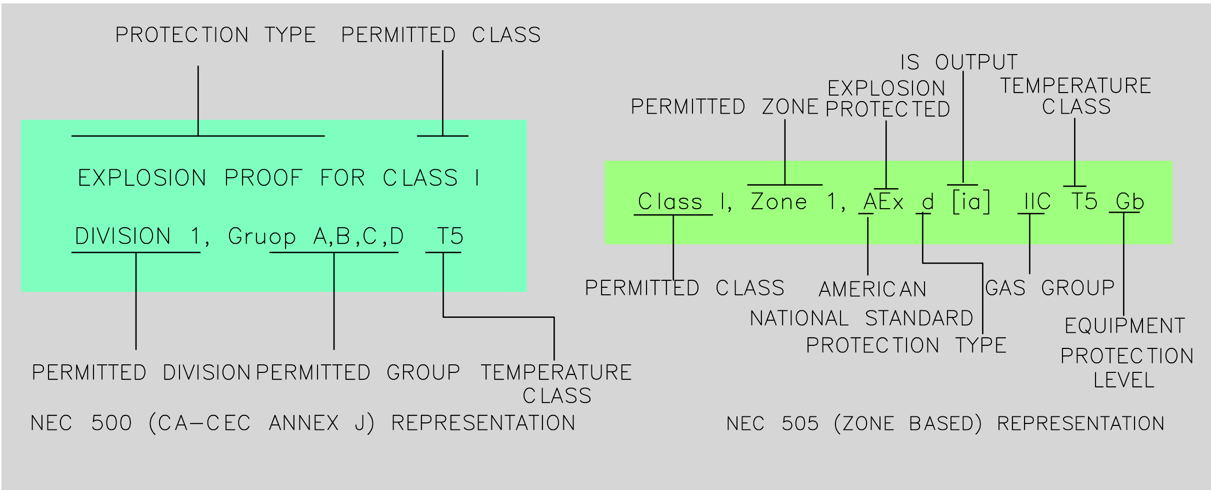


FIGURE AVI/5.0.0-1 Equipment markings (different standards). (A) Equipment marking—EU/IEC. (B) Equipment marking—NEC based.

PROTECTION TYPE	PROTECTION PRINCIPLE	EXPLOSIVE ATMOSPHERE	GEOGRPHICAL LOCATION	STANDARD	CODE
EXPLOSION PROOF	CONTAINS THE EXPLOSION AND EXTINGUISH THE FLAME	CLASS I DIVISION1	USA	FM3615	XP
		CLASS I DIVISION1	CANADA	CSA C22.2-30	XP
FLAME PROOF		CATEGORY 1G/2G/3G	EUROPE UNION	EN 60079-1	EX da/db/dc
		EPL Ga/Gb/Gc	International- IEC	IEC 60079-1	
		CLASS I ZONE 1	USA	ISA 60079-1	AEx d
		CLASS I ZONE 1	CANADA	CSA C22.2-60079-1	Ex d
POWDER- FILLED		CATEGORY 2G	EUROPE UNION	EN 60079-5	Ex q
		EPL Gb	International- IEC	IEC 60079-5	Ex q
		CLASS I ZONE 1	USA	ISA 60079-5	AEx q
		CLASS I ZONE 1	CANADA	CSA C22.2-60079-5	Ex q
ENCLOSED BREAK		CATEGORY 3G	EUROPE UNION	EN 60079-15	Ex nC
		EPL Gc	International- IEC	IEC 60079-15	Ex nC
		CLASS I ZONE 2	USA	ISA 60079-15	AEx nC
		CLASS I ZONE 2	CANADA	CSAC22.2-60079-15	Ex nC
INTRINSIC SAFETY	LIMITED ENERGY OF SPARK AND SURFACE TEMPERAURE	CLASS I DIVISION1	USA	FM3610	IS
		CLASS I DIVISION1	CANADA	CSA C22.2-157	IS
		CATEGORY 1G/2G/3G	EUROPE UNION	EN 60079-11	EX ia/b/c
		EPL Ga/Gb/Gc	International- IEC	IEC 60079-11	
		CLASS I ZONE 1	CANADA	CSA C22.2-60079-11	-DO-
		CLASS I ZONE 1	USA	ISA 60079-11	AEX ia-c
LIMITED ENERGY		EPL Gc	International- IEC	IEC 60079-15	EX nL
		CLASS I ZONE 2	USA	ISA 60079-15	AEX nC
		CLASS I ZONE 2	CANADA	CSAC22.2-60079-15	EX nL
PRESSURIZED	KEEP FLAMMABLE GAS OUT	CLASS I DIVISION1	USA	FM 3620(NFPA496)	TYPE X/Y
		CLASS I DIVISION1	CANADA	NFPA496	
		CLASS I DIVISION2	USA	FM 3620(NFPA496)	TYPE Z
		CLASS I DIVISION2	CANADA	NFPA496	
		CATEGORY 2G	EUROPE UNION	EN 60079-2	Ex px/py
		EPL Gb	International- IEC	IEC 60079-2	
		CLASS I ZONE 1	CANADA	CSA C22.2-60079-2	
		CLASS I ZONE 1	USA	ISA 60079-2	AEx px/py
		CATEGORY 3G	EUROPE UNION	EN 60079-2	Ex pz
		EPL Gc	International- IEC	IEC 60079-2	
		CLASS I ZONE 2	CANADA	CSA C22.2-60079-2	
		CLASS I ZONE 2	USA	ISA 60079-2	AEx pz
RESTRICTED BREATHING		CATEGORY 3G	EUROPE UNION	EN 60079-15	Ex nR
		EPL Gc	International- IEC	IEC 60079-15	Ex nR
		CLASS I ZONE 2	USA	ISA 60079-15	AEx nR
		CLASS I ZONE 2	CANADA	CSAC22.2-60079-15	Ex nR
ENCAPSULATED		CATEGORY 1G/2G/3G	EUROPE UNION	EN 60079-18	Ex ma/mb/mc
		EPL Ga/Gb/Gc	International- IEC	IEC 60079-18	
		CLASS I ZONE 0/1/2	CANADA	CSAC22.2-60079-18	
		CLASS I ZONE 0/1/2	USA	ISA 60079-18	AEx ma/m or mb/mc
OIL IMMERSED		CATEGORY 2G/3G	EUROPE UNION	EN 60079-6	Ex o ob/oc
		EPL Gb/Gc	International- IEC	IEC 60079-6	
		CLASS I ZONE 1	CANADA	CSAC22.2-60079-6	Ex o
		CLASS I ZONE 1	USA	ISA 60079-6	AEx o

FIGURE AVI/5.0.0-2 Comparison of standards and protection concept [3]. *Developed based on FM approval poster.*

LIST OF ABBREVIATIONS

BPCS Basic process/plant control system
EAC Electrical area classification
EPL Equipment protection level
HFT Hardware failure tolerance
LEL Lower explosive limit
PFD Probability of failure on demand
SFF Safe failure fraction
SIF Safety instrumented function
SIL Safety integration level
SIS Safety instrumented system
UEL Upper explosive limit

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[4] Gas Detection Handbook, Fifth ed., MSA, http://www.gilsoneng.com/reference/gasdetectionhandbook.pdf.

APPENDIX VII

DEVICE COMMUNICATION

1.0.0 GENERAL DISCUSSIONS AND HARDWIRED TRANSMISSION

The duties of sensors and transducers are to sense a physical parameter and convert it into an electrical signal (in the modern world only electronic instruments are in use and pneumatic signal transmission is obsolete). This signal will be useful only when it is transmitted and/or communicated to secondary instrument for subsequent action, i.e., any control and monitoring action as necessary could be taken. In the case of flow metering, unless the flow meter signal is transmitted and/communicated to secondary instruments for action, its basic action will not be served. Therefore, it is needless to argue that the role of the transmitter, i.e., device communication, cannot be overestimated. Here I use the word communication specifically because in the modern world there can be wireless communications also, so instead of transmission I preferred the word communication which could be through a wire or wireless. There are various ways in which flow meters/transmitters can communicate with the rest of world. This could be simple hardwired communication, transmission protocols, or communication through a fieldbus (may be wireless also). Since in many cases the flow instruments will be in a hazardous location, it is necessary to take necessary action so that even under hazardous conditions the device can operate unaffected. Necessary protection through enclosures has already been discussed in Appendix VI, which does not cover the safe fieldbus system. Therefore, in this appendix the safe fieldbus system shall also be covered. We begin our discussion by addressing all these one by one.

Various ways and means used for flow device communication include but are not limited to the following:

- Hardwired communication;
- Link and protocol [1];
- Fieldbus communication [1].

This appendix has been developed with help of the author's books entitled "Power Plant Instrumentation and Control Handbook" and "plant Hazard analysis and safety instrumentation systems (approved by IChemE U.K.)" published by Elsevier. Courtesy of Elsevier USA.

1.1.0 Current Loop—Hardwired Transmission

A 4–20 mADC signal is the most popular electronic signal transmission in hardwired form. It is not that other types cannot be used, such as 0–10 VDC 0–50 mADC signals have been found to be used. Before going into further details let us look into the details about 4–20 mADC loop and understand the transmission process.

1.1.1 CURRENT LOOP AND SELECTION FOR 4–20 MADC

In this section discussion will be on why current signal is chosen in place of voltage and why 4–20 mA has been chosen.

1. **Current signal:** From Ohms law it is clear that when there is current flow through the resistance there will be a voltage drop across the resistance equal to the resistance times current value passing through the resistance. Naturally, instead of current if the voltage value were chosen for the transmitter for the same value of output from the transducer the receiver would receive output which would vary depending on the distance between the transmitter and receiver on account of resistance in the wire. This means keeping all conditions the same, if the transmitter sends a signal, the receiver nearer to the transmitter would receive more signal for the same physical input, than the receiver at a far away place on account of additional resistance of the connecting wire. In contrast, in the case of a current loop the receiver and transmitter would have to be in series and the same signal would pass through the receiver and would not change (only if the proper power supply is chosen, as discussed later) unless the distance is too long. Therefore it could be argued that current transmission is preferred to voltage transmission.
2. **4−20 mA:** From here it is clear that this output means the lowest value of span would give 4 mA and the highest value of span would give 20 mA. This means this is a live zero signal, meaning that for a flow of e.g., 0−100 m^3/h when there will be zero flow then output will be 4 mA and at 100 m^3/h, 20 mA. This means this is a live zero. It has two advantages.
   - *4 not zero:* If the signal line is snapped then current will be zero, not 4 mA. This means it is possible to distinguish between actual zero physical input (flow) and power supply failure or cable snapping. As in the case of zero flow, output would be 4 mA when there is no cable snap or power supply failure. In case of power supply failure/cable snap output will be zero. So, it is failsafe. Also, live zero gives a better signal to noise ratio [2].
   - *Two-wire loop power:* In case of two-wire loop power, operation would not be possible, if there is no current flowing in the loop (0 mA), that no power for the instrument to keep its circuitry active. In order to use an instrument on a loop that has 0 mA or 0 VDC as the low end, the power for the instrument would have to come from a separate source, which would require a three-wire or four-wire instrument.
   - *Why 4−20 mA:* Typical electronic signal types could be:
     4−20 mA (low end = 20/5 = 4, span = 4 × 4 = 16);
     10−50 mA (low end = 50/5 = 10, span 4 × 10 = 40);
     1−5 VDC (low end = 5/5 = 1, span = 4 × 1 = 4).

   Of these the third one is voltage transmission and this is not acceptable for long distance transmission, on account of the issue discussed above. Instead of 4−20 mADC it could be 10−50 mADC also. Normally at the receiver, the current is converted into 1−5 VDC. So, in the case of 4−20 mA, 250 Ω resistance would be necessary. On the other hand, 100 Ω resistance would be necessary. Naturally, in the case of 4−20 mA the energy will be lower and is preferred for intrinsic circuits.
3. **DC not AC:** DC signal is inactive for capacitance. On the other hand, the AC signal attenuates in the presence of capacitance so AC is vulnerable to stray capacitance and capacitance of the cable, i.e., it is less sensitive to electrical noise.

1.2.0 4−20 mADC Current Loop Discussions

In its simplest form, in a 4−20 mADC current loop at least three components are essential. These are the power supply, transmitter, and receiver. Let us look into these closely.

1.2.1 POWER SUPPLY IN A CURRENT LOOP

The current loop uses DC power supply. As discussed earlier, in the case that AC power would have been used in the loop, then the magnitude of the current would be continuously

changing, also there will be stray pickup, making it difficult to discern the signal level being transmitted. For 4–20 mA current loops with two-wire transmitters, the standard and most common loop power supply voltage is 24 VDC. However, there may be use of 12, 15, and 36 VDC also. The most pertinent and important issue here is that power supply must be set to a level that is greater than the sum of the minimum voltage required to operate the transmitter, plus the IR drop in the receiver. It is to be noted that although transmitters regulate the current in the loop, the voltage at its output terminals will vary according to the loop power supply voltage, the IR voltage drop in the wires, and the IR voltage drops across the receiver (at maximum current signal should be considered). Therefore, one has to ensure that the loop supply voltage level can meet the minimum requirements mentioned. The voltage drop wire is normally not a concern, as the voltage drop of a section of wire is minuscule. However, over long distances of *over* 300 m, it can add up to a significant amount, depending on the thickness (gage) of the wire. At times there could be a shortfall in the power supply due to a power supply voltage that can no longer drive the necessary loop voltage due to an added load in the current loop [2]. For this reason, transmitter manufacturers provide a load versus power supply curve so that based on application suitable voltage can be adjusted. However, this can happen because of any one (or combination) of the following reasons:

1. Long distance (IR voltage drop in the wires);
2. Simply failing to include the over-range current;
3. Addition of too many receivers, or loads in the loop.

1.2.2 TRANSMITTER IN CURRENT LOOP

This is the device used to transmit a signal from a sensor over the current loop. There can be only one transmitter output in any current loop. It acts like a variable resistor with respect to its input. The transmitter uses 4 mA output to represent the calibrated lowest end of span and 20 mA to represent the calibrated highest end of span 4–20 mA current loop. A common misconception is that the transmitter is the source of the loop current. It is not the source of the current. Actually it is a series-connected current-sinking circuit that draws current from a power supply wired to its output terminals. The current flowing through the transmitter is proportional to the input signal being measured. The current signal on the loop is regulated by the transmitter according to the sensor's measurement.

1.2.3 RECEIVER IN CURRENT LOOP

At the receiver an analog 4–20 mADC signal current is normally converted to a voltage input with a precision resistor. By using 4–20 mA as the driver, the voltage produced across a load resistor is easily scaled by simply changing the resistance. Common resistances used are 250 Ω (1–5 V), 500 Ω (2–10 V), 50 Ω (0.2–1 V), and 100 Ω (0.4–2 V). Depending on the source of current for the loop, receiver devices may be classified as *active* (supplying power) or *passive* (relying on loop power). These receivers can be input of PLC or DCS. They can be sourcing or sinking types.

1.2.4 CURRENT LOOP TYPES

As the name implies, there should be a loop, which refers to the actual wire connecting the power supply, sensor/transmitter to receiver (the device receiving the 4–20 mA signal), and then back to complete the current loop. As per ANSI/ISA standard 50.00.01; there can be three different current loop connection types as depicted A, B, and C in Fig. AVII/1.2.4-1. These diagrams are self-explanatory. A brief description of Fig. AVII/1.2.4-1 has been presented.

1. **Diagram A:** A two-wire transmitter where the transmitter is floated with respect to the ground which is shared commonly by the receiver and power supply. Loop-powered two-wire transmitters have their power supply and signal sharing the same pair of connection wires. This simplifies installation considerably, and

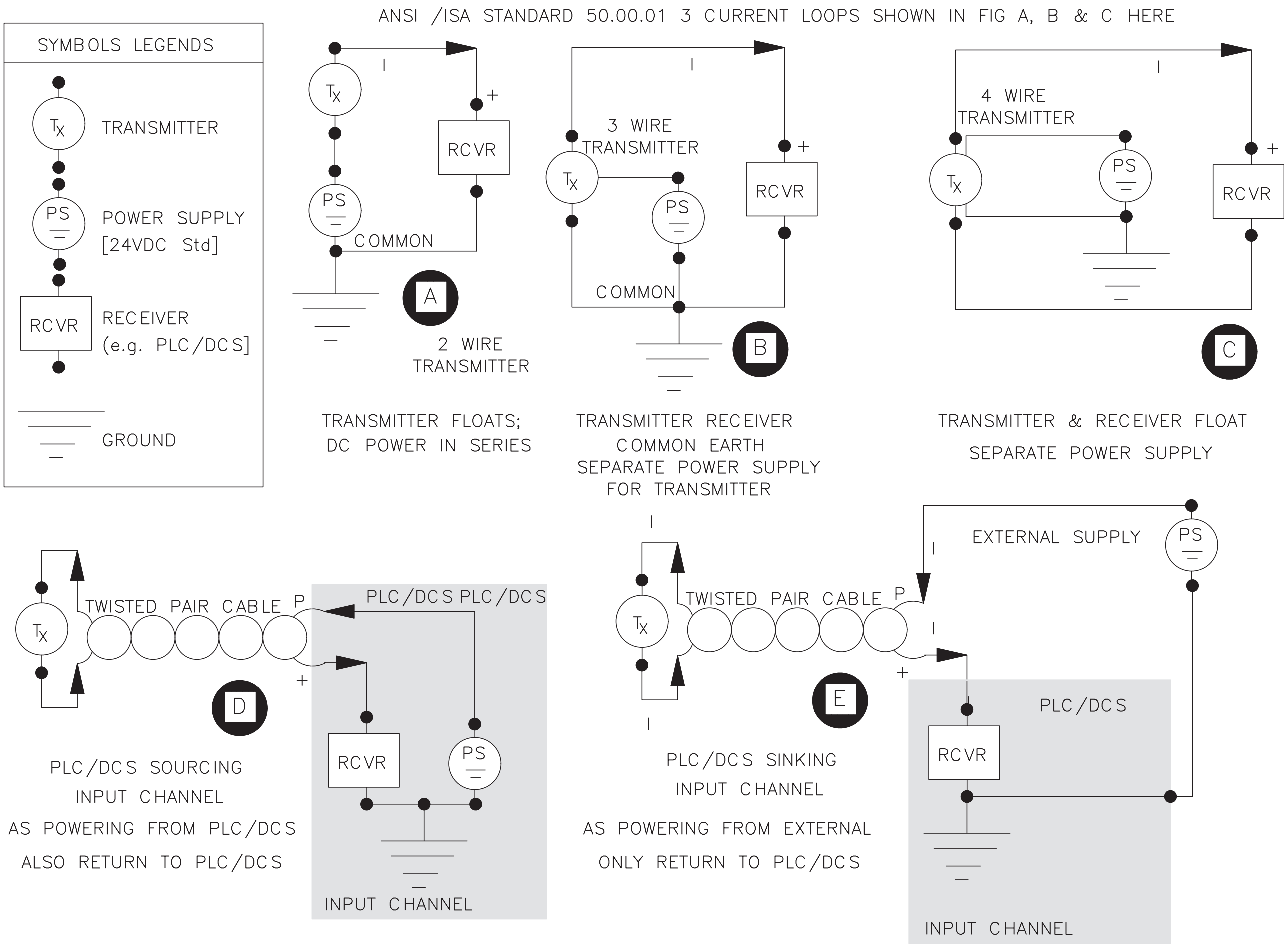


FIGURE AVII/1.2.4-1 Current loop transmission types.

the low DC transmission levels permit the use of small, inexpensive copper wiring.

2. **Diagram B:** Here the transmitter, receiver, and power supply share the same ground. There is a separate wire for the power supply to the transmitter and it is a three-wire type of connection.
3. **Diagram C:** This is a four-wire connection complete with two separate wires for the power supply and transmitter. In the signal side both the transmitter and receivers are floating type.

   There are other sets of connections shown in D and E in Fig. AVII/1.2.4-1. As mentioned in regard to the receiver above, for PLC/DCS that input can be sourcing or sinking type.
4. **Diagram D:** This is a sourcing type because the power supply is within the input of PLC/DCS. So, PLC/DCS input sends power supply and gets back the current as the return path due to the common ground point.
5. **Diagram E:** This is a sinking type as there is an external power supply source and current returns to PLC/DCS input in a return path to sink the signal using common ground. The signal is sensed in the sinking path.

1.3.0 Other Hardwire Signal Types

Contact output and pulse type are two other signals also available from flow meters.

1. **Contact/binary output:** These are normally potential contacts of suitable rating or can be open collector type output also. They are mainly used for control and status indications. They are used in the event of a dangerous condition, e.g., device failure or an alarm and are used mainly to indicate possible changes in the

course of the process. Flow switches and limit value monitors give this type of output.

2. **Pulse signal:** Pulse outputs are common with flow meters. Pulse output signals are proportional to the volume flow rate and can be integrated by a totalizer to arrive at the total volume over a time period. Meter K factor discussed in the main text accounts for the proportionality constant for the meter pulse rate and volume flow. In this manner a volume signal is generated from the flow rate. The totalizer indicates the total volume that has flowed through the flow meter during a specific time interval [8].

2.0.0 LINK AND PROTOCOL

During the discussions on flow meters and associated converters or electronics that some of them, e.g., thermal mass flow meter provide, in addition to hardwired output, RS links for data transfer via, e.g., MODBUS. Highway Addressable Remote Transducer (HART) is quite common with standard process transmitters as well as most modern flow meters. In this section brief discussions on various links and protocols shall be discussed. The discussion starts with important links available for communication.

2.1.0 Important Links for Device Communication

These links are referred to as recommended standard (RS) or (later modified by Electronic Industries alliance) (EIA), i.e., RS (EIA232).

2.1.1 LINK RS (EIA) 232

RS 232 has been defined as an electrical interface for serial transmission of data over a short distance for point-to-point communication. This link is connected in master–slaves (multiple) mode with normal communication rate <20 kbps. Nowadays, however, faster ones are also available, e.g., MAX3225E. Since these are connected in a daisy chain, a major disadvantage is that if there is a break (as shown by dotted break line) in the chain, all downstream devices will be disconnected. Major features include but are not limited to the following.

1. **Electrical characteristics and data include the following:**
   - *Binary 0:* +5 to 15 VDC(Tx) and +3 to 13 VDC(Rx);
   - *Binary 1:* (−)5 to 15 V(Tx) and (−)3 to 13 VDC(Rx);
   - Slew rate is 4–30 V/μs;
   - ~*Load/output resistance:* 3–7 kΩ/300 Ω;
   - Start bit binary 0; stop bit binary 1;
   - Data 5–8 bit;
   - Parity even, odd, mark, or space;
   - *Leading and trailing idle bit:* binary ones.
2. **Connection:** Plugable connector and defined pin and function.
3. **Interface:** Interface circuit for communication.
4. **Cabling and connections [1]:** The standard does not define *external power supply, character encoding* (say ASCII), *protocol*, *framing character,* and *error checking method*, etc. Also there is no guideline for cable selection. **9/25** D plug connectors are used.

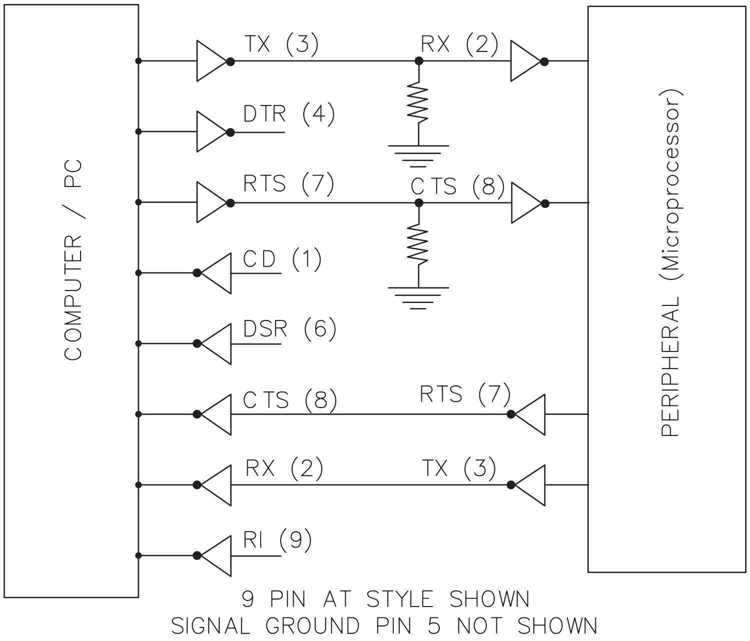
   For connection details on RS 232, Fig. AVII/2.1.1-1 may be referenced.

2.1.2 LINK RS (EIA) 422

Fig. AVII/2.1.2-1 depicts a typical connection for RS 422. Fig. AVII/2.1.2-1A shows a balanced interface applicable for RS 422 (also RS 485). Fig. AVII/2.1.2-1B details a master–slave connection.

It is a balanced voltage interface with better baud (100 K) rate and distance (1.2 km), in comparison to RS 232. The baud rate falls in logarithmic scale with an increase of distance (maximum 10 Mbps is possible for 12 m typical for 24AWG twisted pair cable). It can be used in point-to-point interconnection of digital equipment. A single master can accommodate up to 10 slaves via RS 422 interface. Typical features are listed here:

1. **Open circuit O/P voltage:** ±10 VDC (maximum);
2. **CMV:** @ R_L 100 Ω: ±3 V;



PIN	CODE	DETAILS
1	CD	CARRIER DETECT
2	RX	RECEIVED DATA
3	TX	TRANSMITTED DATA
4	DTR	DATA TERMINAL READY
5	GR	SIGNAL GROUND
6	DSR	DATA SET READY
7	RTS	REQUEST TO SEND
8	CTS	CLEAR TO SEND
9	RI	RING INDICATOR

FIGURE AVII/2.1.1-1 RS 232 connection details (TYP).

3. **Loaded O/P voltage:** +2 VDC (minimum) (R_L 100 Ω);
4. **Differential receiver voltage:** ±10 V(±12 V capability);
5. **Maximum out current:** 150 mA;
6. **Receiver input resistance:** 4 kΩ.

2.1.3 LINK RS (EIA) 485

On account of transmission over twisted pair (***half duplex***—bidirectional communication but not both at the same time) cabling, RS 485 is less costly, and less sensitive to noise at the same time, it allows bidirectional asynchronous serial transmitter over a long distance of **1.2 km** at a baud rate of **100 kbps** (in 10 m maximum of 35 Mbps is possible). Unlike RS 422, it can accommodate multiple node (up to **32**) linear topologies in *peer-to-peer communication* [1]. RS 485 is available in a four-wire connection in *master–slave* mode and for *duplex* communication (like RS 422). For master–slave connection details, Fig. AVII/2.1.3-1 may be referenced.

Grounding is a very important cable termination as with suitable resistance it can avoid data loss. It has nine pins in D a SUB plug connecter. RS 485 also finds its use in many protocols for electrical interface, e.g., MODBUS, PROFIBUS. Major features including specification are as follows:

1. **Open circuit O/P voltage:** 1.5–6 VDC(±);
2. **Short circuit out current:** ±250 mA per output;
3. **Receiver sensitivity:** (−)7 < V < 12: ±200 mV;
4. **Receiver input resistance:** >12 kΩ;
5. **Common mode voltage:** ±3 V;
6. **Loaded O/P voltage:** 1.5–6;
7. VDC(+/)@ R_L 100 Ω.

2.2.0 MODBUS Protocol

In 1979 this protocol was developed by Modicon for their PLC. Later it was used by various devices including flow-metering devices and associated electronics for data communication. As shown in Fig. AVII/2.2.0-1A, it is a protocol on application layer. The workings of MODBUS protocol in master–slave mode has been depicted in Fig. AVII/2.2.0-1B.

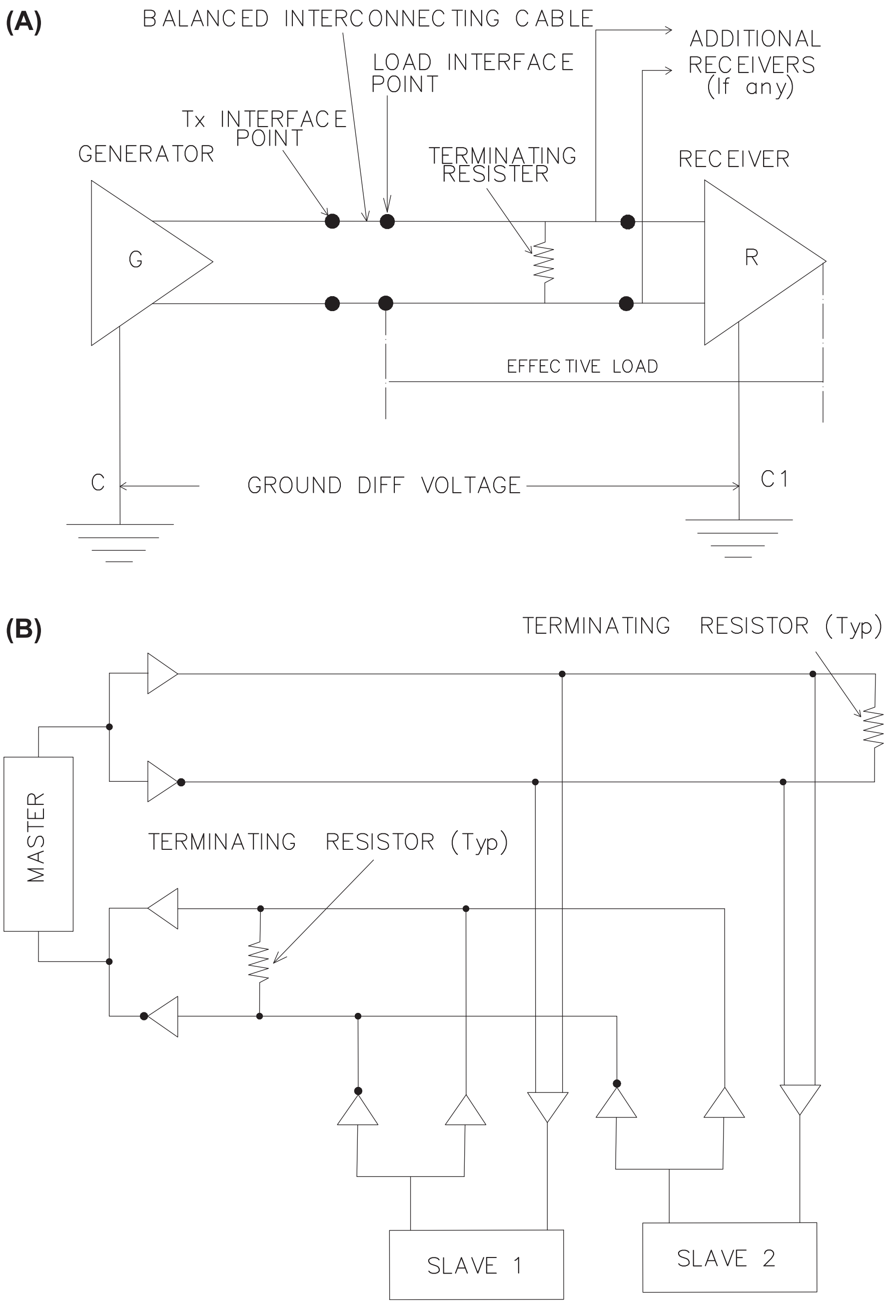


FIGURE AVII/2.1.2-1 RS 422 connection details. (A) Balanced interface RS 422. (B) RS 422 in master–slave connection.

2.2.1 TRANSACTION METHODOLOGY

Transaction methodology in MODBUS has two types, i.e., *MODBUS network* and transaction with a *different kind of network.*

1. **MODBUS network:** In the former method the master has established a data format for the master's query by placing "*Device address*, a '*function code*' defining the action, any '*data*' to be checked and '*error*' checking field. Slave message in MODBUS protocol contains field '*confirming action*,' any '*data*' to be returned and 'error' checking field."
   - *QUERY: Function code* tells the slave (being addressed) the action to perform and any additional information, *Data byte* field

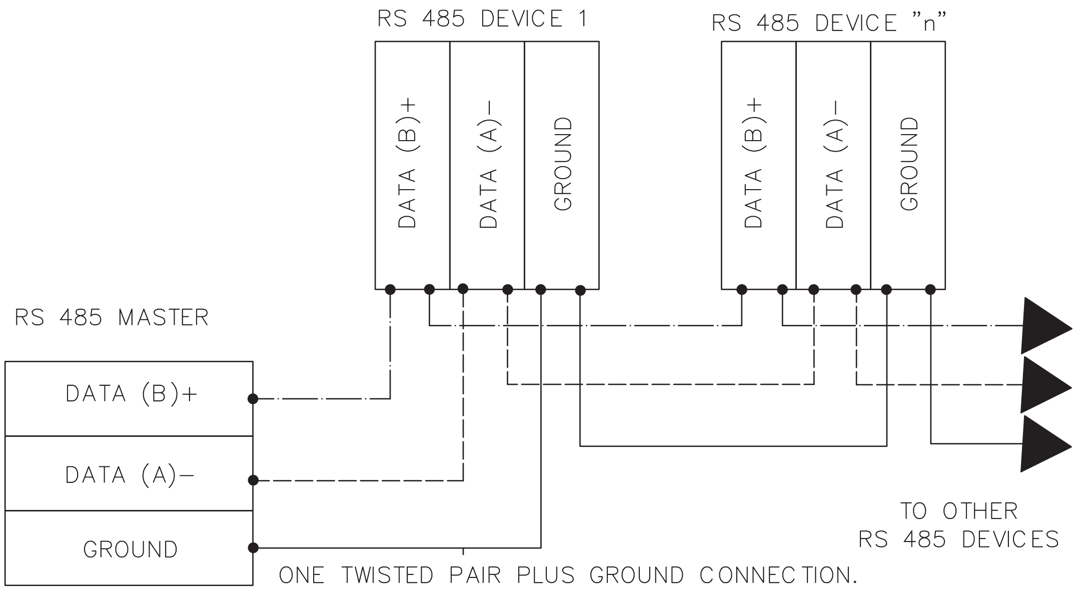


FIGURE AVII/2.1.3-1 RS 485 master–slave connection details (maximum 32 nodes).

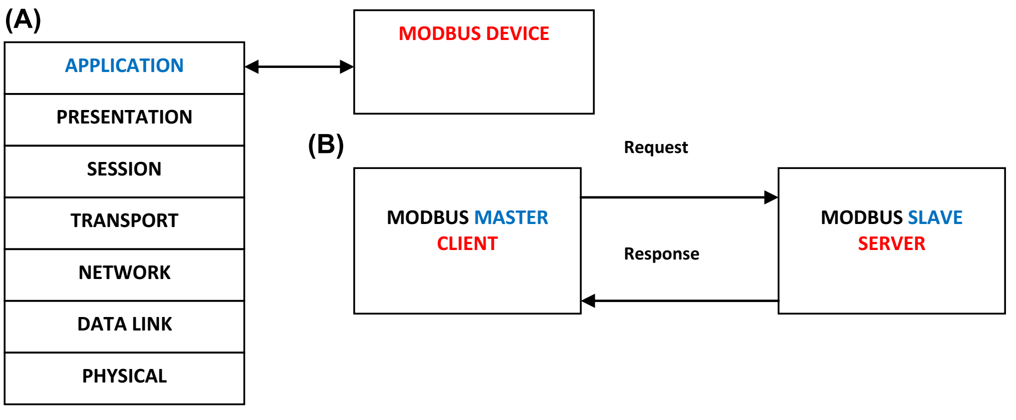


FIGURE AVII/2.2.0-1 MODBUS system [1]. (A) MODBUS interface. (B) MODBUS communication.

information to slave regarding register to start and how many registers to read, etc. *Error* check is for the slave to validate the data.

- *RESPONSE: Function* code echoes the function code in query. *Data byte* contains the data collected. In the case of *Error* Function code is modified to indicate error.

2. **Different network:** For *different networks* it uses a built-in port, network adapter, etc. to communicate in "peer-to-peer" communication mode. In that case the master initiates the request.

MODBUS communication is based on a packet of data called the protocol data unit (PDU) comprising query and response as discussed above. There is another PDU known as exception response PDU to indicate an error.

2.2.2 IMPLEMENTATION METHODS

MODBUS has been implemented in all physical media such as wire, fiberoptic, and radio communication. They are mainly implemented utilizing:

- SERIAL ASYNCHRONOUS Master–Slave;
- IP Master–Slave.

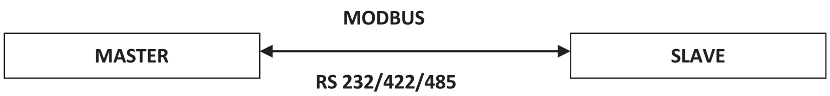


FIGURE AVII/2.2.2-1 Point-to-point communication between master and slave.

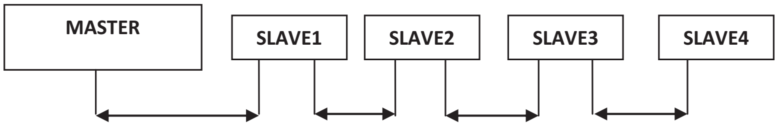


FIGURE AVII/2.2.2-2 Multiple–slave communication in RS 485.

FIGURE AVII/2.2.2-3 IP method of MODBUS implementation.

1. **Serial link:** RS 232 (EIA232): Valid for ***short distance (say 15 m)*** and ***point-to-point*** communication RS 422: this link can be used for ***bidirectional*** communication over a comparatively ***longer distance (<1.2 km)*** in ***point-to-point*** mode, as shown in Fig. AVII/2.2.2-1
2. **RS 485:** As shown, both Figs. AVII/2.2.2-1 and AVII/2.2.2-2 are applicable for RS 485. In actual implementation, the protocol data unit (PDU) is transformed into an application data unit (ADU) by adding a header and error check sum having a maximum of 256 bytes, as shown in Fig. AVII/2.2.2-3.
3. **IP-based:** In a TCP/IP-based MODBUS implementation with multimaster system, bidirectional communication is possible. It uses TCP/IP stack for communication and extends the PDU with an IP-specific header.

There exist two methods of serial communications, **ASCII and RTU**, with different encoding [1].

2.3.0 HART Protocol

Highway Addressable Remote Transducer (HART) is an open, bidirectional communication protocol, utilizing *frequency shift keying* (FSK) protocol to exchange data between intelligent field devices with the host system. In the true sense HART is ***not*** a fieldbus but a protocol used for various transducers. In HART technology 4–20 mADC signal can be sent simultaneously with digital information in a superimposed manner. Fig. AVII/2.3.0-1 may be referred to for HART protocol details.

2.3.1 HART PROTOCOL FEATURES

The major features of popular HART protocols are described here:

1. **Technological advantages:** It has technological advantages to support the user:
   - *Wiring:* Standard wiring for 4–20 mADC, but also digital data transmission;
   - *Usefulness:* Complete usefulness of intelligent devices to improve operational performance;
   - *Warning:* Early warning generation for variation in performance of process, device;
   - *Troubleshooting:* Quick troubleshooting by identification and problem resolution;
   - *Validation:* Continuous validation of loop integrity and automation strategy;
   - *Gateway:* Gateways to communicate with field buses.

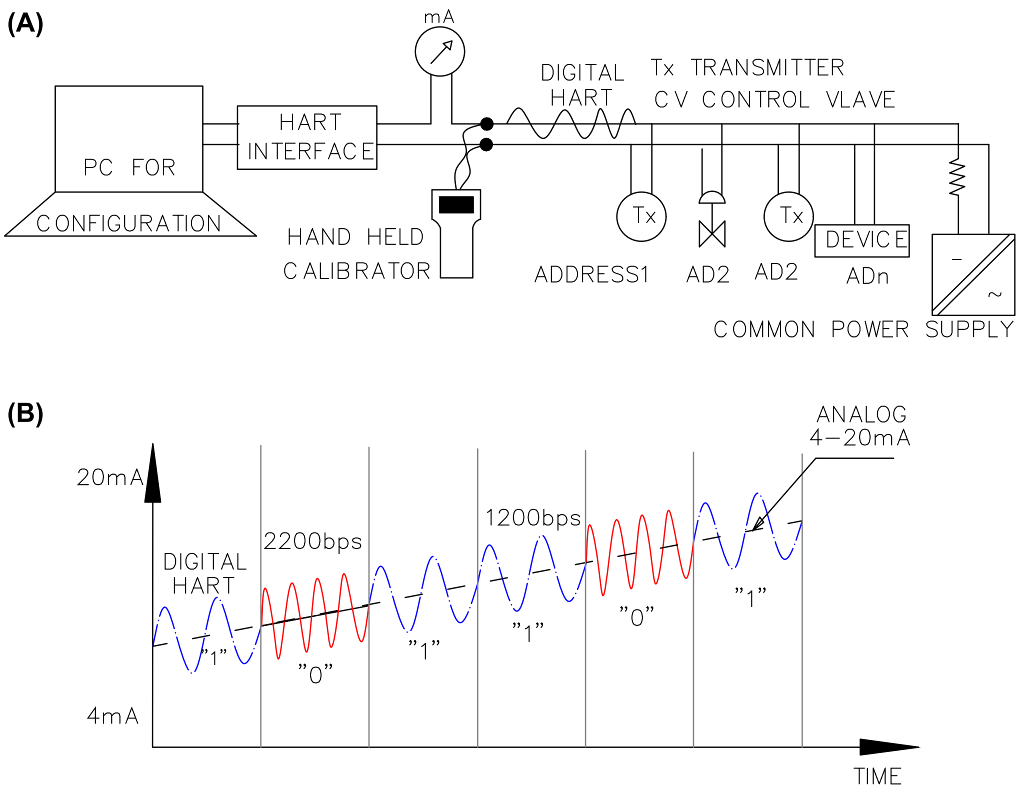


FIGURE AVII/2.3.0-1 HART protocol details. (A) HART communication analog and digital with multidrops. (B) HART superimposition of digital over analog.

2. **System and plant availability features:** System availability issues include the following:
   - *Risk reduction:* Robust and accurate protocol for risk reduction for failure as well as avoidance of costly shutdown of the system;
   - *Connection issue:* Ability to detect device and connection problem in real time and early warning of deviations;
   - *Integration:* Ability to integrate devices and systems.
3. **Diagnostics and maintenance cost:** Quick validation of the loop and configuration, so any change quickly reported for action coupled with remote diagnostics (at the host!).
4. **Miscellaneous issues:** The following are some important issues worth noting:
   - Regulatory compliance;
   - Integrated safety level (SIL);
   - Cost-effectiveness;
   - Enabled for record keeping and possibility to test shutdown condition;
   - Broader selection of product from multiple vendor support.

2.3.2 HART PROTOCOL CHARACTERISTICS

The following are major characteristic features associated with the HART protocol:

1. **Technique:** Superimposition of digital signal ***with*** 4–20 mADC signal;
2. **Technology:** Bell 202 standard FSK;
3. **Communication Speed:** 1200 bps;
4. **Number of devices support (in loop):** Could be as many as 100 but based on allowed

load impedance it is typically 15. Powering provision and contributor of noise from each put a limit on the number of devices in a loop;

5. **Configuration:** Master—slave mode. It can support two masters, e.g., the host being a primary master and handheld configurator can be a secondary master, whereas intelligent devices, e.g., Tx/Control valves could be the slaves, as shown in Fig. AVII/2.3.0-1A;
6. **Communication modes:** Peer-to-peer, multiplexing type, with one PC, being connected via a multiplexer or it can be a multidrop type configuration [1]. Refer to Fig. AVII/2.3.0-1A;
7. **Cable:** Normal instrumentation twisted pair cable is sufficient. Depending on the distance coverage the specification may change, e.g., up to 1500 m standard conductors with a common shield, whereas for distance ~3000 m the same cable but with an individual shielding. For shorter distances unshielded cables may be possible, however, it is recommended to use screened cables;
8. **Data exchange:** Status, diagnostics, calculated value, etc. Some of the generic parameters are: PV reading, analog output reading, secondary variable reading, change (tag, data, PV unit, range, damping, output transfer function, polling address), output trimming, loop checking data, zero and range change, modem action, etc.;
9. **Load limit:** 1100 Ω, provision of powering the entire loop;
10. **Noise immunity and error detection:** On-line devices can be added or removed without much degradation of performance. Noise immunity conforms to IEC 801-3 (*Radiated, radio-frequency, electromagnetic field immunity)* and IEC 801-4(*Electrical fast transient/burst immunity*) Class 3. It can detect up to three corrupt bits in a telegram as error detection;
11. **Hazardous application:** IS compatible and Exi (standard code);
12. **Addressing:** Special long format addressing format is used. During configuration mode in peer-to-peer mode tag and bus address are set.

2.3.3 WIRELESS HART PROTOCOL

The HART protocol is extremely helpful for device communication and less costly on account of two-wire connections. Since it also supports 4—20 mADC superimposed it is easier for retrofitting. Typical wireless HART network has been depicted in Fig. AVII/2.3.0-2. HART Communication Foundation in September 2007 developed and introduced wireless HART with same outstanding features of well established HART protocol discussed. Wireless HART implements a wireless mesh communications network for process automation applications maintaining compatibility with existing HART devices, commands, and tools. Wireless HART network includes three main elements:

- Wireless field devices;
- Gateways for enabling communication field devices and host applications of plant network;
- Network Manager responsible for configuring the network, managing message routes and scheduling communications.

It utilize 2.4 GHz bandwidth and follows standards like IEC 62591, IEEE 802.15.4. It supports direct sequence spread spectrum technology and TDMA synchronized.

However, for system integration, fieldbus is extremely important and many systems can be integrated (refer to Chapter VII of Ref. [1]). The following section deals with the fieldbus system.

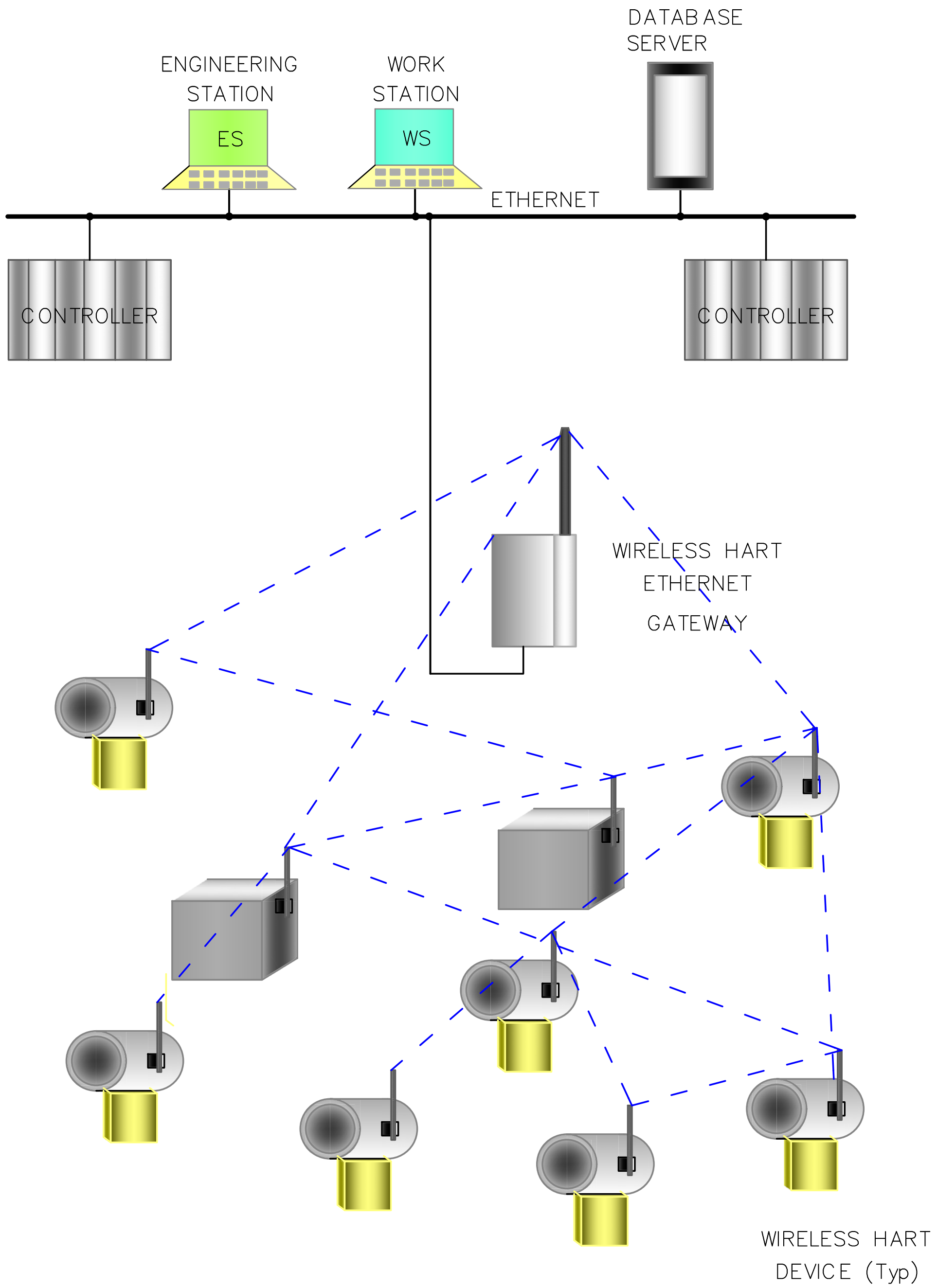


FIGURE AVII/2.3.0-2 Wireless HART network.

3.0.0 FIELDBUS SYSTEM AND SAFE FIELDBUS

Fieldbus can be conceived as a digital communication system meant for field devices such as sensors, actuators, and field control systems. Fieldbus addresses a few issues, like device addressing, two-way communication for data exchange pertinent to parameters, as well as status of the field device, and communication speed to name a few. Therefore, it is not justified to look at a fieldbus cable "***JUST WIRE***." In an integrated system it can be compared with one of the ***main arteries*** in the human body. The following are a few features in favor of fieldbus [1]:

1. Significant reduction in cable & cable tray;
2. Less cable tray layout means lower space requirement;

3. Easy to use & future expansion and/or modification;
4. Extensive data exchange at faster rate to & from the field devices;
5. Reliable, cost effective and deterministic;
6. Greater Flexibility in system design & layout;
7. Open interface for integrating multiple products from different vendors in a system.

3.1.0 Fieldbus Requirements

IEC 61158-2 standard has been developed with the view of an interconnection of various automation system components. Some of the salient features of IEC 1158-2 related to transmission technology have been presented in Table AVII/3.1.0-1 IEC 1158-2 Features.

3.2.0 Safe Fieldbus in Hazardous Applications

Fieldbus devices, being low-power devices, require intrinsic safety (IS) for fieldbus installations in hazardous areas. The following are distinct features found in fieldbus intrinsic applications:

- There can be several devices connected through a single barrier;
- Several barriers may be used for a single device;
- The same segment may have IS as well as other devices;
- Like in a conventional system, a fieldbus has the same philosophy of limiting energy. Fieldbus IS has more flexibility and is cost-effective.

There are several approaches for fieldbus explosion protections. These are [5] listed here.

IS barrier for fieldbus:

1. Entity model;
2. Fieldbus intrinsic safety concept (FISCO);
3. High-power trunk (HPT) concept;
4. Dynamic arc recognition and termination (DART);
5. Fieldbus nonincendive concept (FNICO).

Short discussions on the same have been presented below.

3.2.1 IS BARRIERS IN FIELDBUS

In a typical fieldbus installation, 10–12 fieldbus devices are connected via one cable with a length of up to 1900 m in trunk and spur topology, as shown in Fig. AVII/3.2.1-1A. This single cable needs to support power and communications. It is recommended to use short-circuit protection and energy limitation to isolate any fault conditions. Typically, **110 mA** is allowed in gas groups A and B and 235 mA in groups C and D [4]. Various devices (at 24 V power supply) like process transmitters (20 mA), temperature transmitters (16 mA), valves (25 mA), and flow meters (10 mA) have different current consumptions (typical current consumption indicated in parentheses). Therefore, it is necessary to combine the numbers of all these devices to make sure that the maximum allowed current is not exceeded. Maximum cable length, from a voltage drop point of view, is also an important consideration.

TABLE AVII/3.1.0-1 IEC 1158-2 Features

Features	Requirements	Features	Requirements
1. Data transmission	Digital Manchester bit synchronized	5. Data security	Preamble, error free start and end delimiter
2. Speed	31.25 kbps voltage	6. Cable	Two-wire shielded twisted pair
3. Explosion protection	IS EExia and ib EEx d/m/p/q	7. No of station	32/segment(Maximum could be 126 addresses available)
4. Topology	Line/tree or combination	8. Repeaters	Four

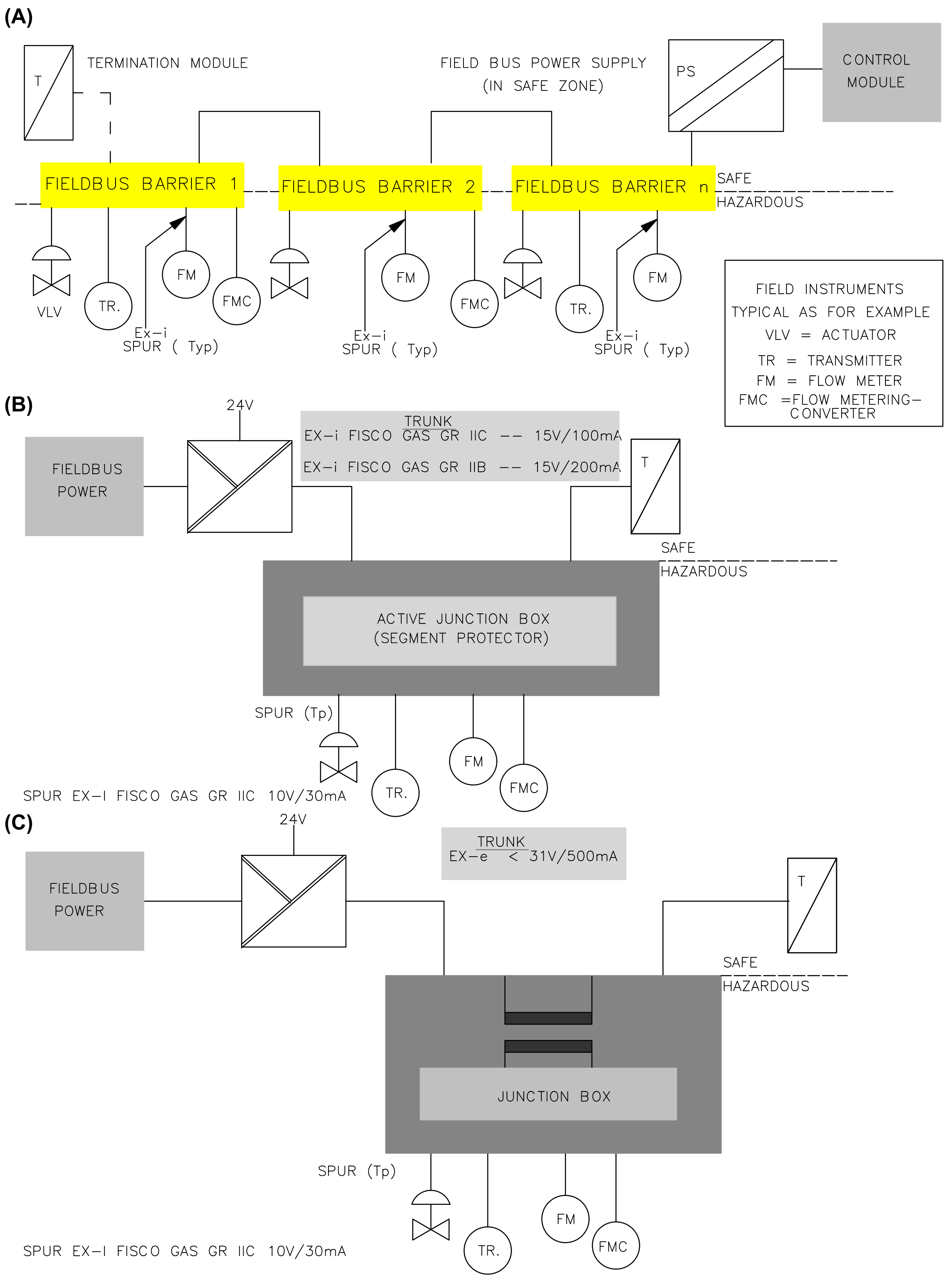


FIGURE AVII/3.2.1-1 Fieldbus intrinsic safety. (A) Multiple barriers fieldbus connection (typical). (B) FISCO concept. (C) HPT concept. *(B) Developed based on an idea from I.G. Kegel, Foundation fieldbus topologies for intrinsic safety (IS) installations, in: Foundation Fieldbus End User Council Meeting; Middle East; Maltaqa, Pepperl+Fuchs GmbH, 2007. Courtesy Peperl+Fusch and foundation fieldbus.*

3.2.2 ENTITY MODEL

The entity model defined in IEC 60079-1 for use of intrinsically safe parameters for validation of IS of a fieldbus. The entity model considers that all electrical parameters of the wire are concentrated at the point of a fault and the electrical wire is a source of energy. In this method, 83 mA maximum current and 18.4 V maximum voltage are allowed. This model is not very popular.

3.2.3 FIELD INTRINSICALLY SAFE CONCEPT (FISCO)

As shown in Fig. AVII/3.2.1-1B, the topology provides isolation for intrinsically safe area equipment, i.e., isolation between safe and hazardous areas. Here, various field devices are connected to an active junction box with Exi spurs and ExI FISCO trunk cable. In the topology of FISCO, there are active junction boxes that have segment protectors (current-limiting devices). There are active junction boxes with foldback short-circuit protection. Current limit is 200 mA @ 17 V for group IIB. Suitable selection is important. These isolate a single short circuit from affecting the entire network. Various features FISCO are as follows [1]:

1. Each segment shall have one power supply;
2. No power fed to the bus when a station is sending;
3. In steady state all field devices consume constant current;
4. Field devices are passive current sinks;
5. The passive line termination at both ends of the main bus line;
6. Linear, tree, and star topology allowed.

3.2.4 HIGH-POWER TRUNK (HPT) CONCEPT

Unlike FISCO, in high-power trunk power supply redundancy is possible. In this method, Exe has been considered for the trunk connection cable. This topology provides the highest possible cable length and at the same time supports the largest number of field devices per segment. The current limitation is higher at 500 mA @ 31 V.

3.2.5 DYNAMIC ARC RECOGNITION AND TERMINATION (DART)

According to IEC 60079-11 a circuit is considered intrinsically safe when "electrical energy within the apparatus and of interconnecting wiring exposed to the potentially explosive atmosphere is restricted to a level below that which can cause ignition by either sparking or heating effects." DART detects the characteristic behavior of a spark, especially the sharp current change di/dt in the initial phase and extinguishes the spark before it becomes incendive. In this connection, the curve in Fig. AVII/3.2.5-1A may be referred to. It uses E_{xi} in both the trunk and spur. Power supply redundancy is possible. The current limit is 35 mA @ 24 V.

3.2.6 FIELDBUS NONINCENDIVE CONCEPT (FNICO)

This is applicable for zone 2 or division 2 hazardous areas, where the explosion hazard is expected to exist only in abnormal circumstances. Here, Ex nL (refer to Appendix VI) is used and is applicable for zone 2 applications. The major components are FNICO power supply, field cable, and field cable termination devices. Power supply connections to the host control system are made at its "safe area" terminals, and those to the field trunk at its "hazardous area" terminals. It also includes the necessary functions for a reliable fieldbus with those of an energy-limited interface. This incorporates a repeater function, connections for 24 VDC supply input, and a switchable terminator [6]. Field terminators take the form of a DIN rail-mounted terminal module. In an FNICO system, the requirements are simple: the wiring hub and its enclosure must be certified for zone 2 or division 2 as appropriate, and be suitable for the environment. Various systems are compared with standard parameters in Table AVII/3.2.6-1.

Foundation Fieldbus and Profibus are most popular amongst the various fieldbus systems available. These fieldbus systems are used by a wide range of flow meters, flow converters, and other field devices. These two types shall be covered in the subsequent discussions.

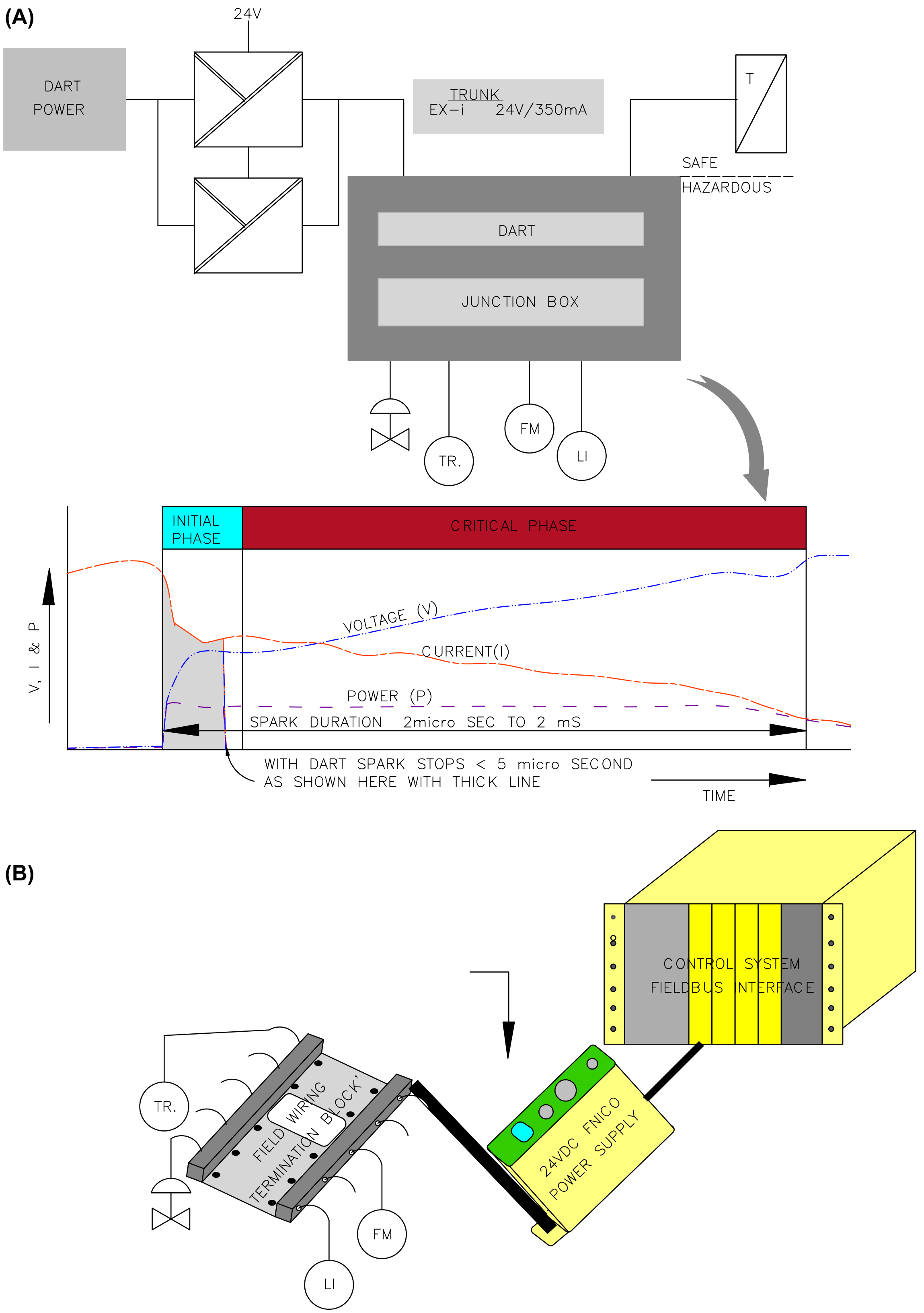


FIGURE AVII/3.2.5-1 DART and FNICO for fieldbus protection. (A) DART system with characteristic curve [5]. (B) FNICO connection system (for zone 2) [5].

TABLE VII/3.2.6-1 Comparison of Various Fieldbus Protection Concepts [7]

Fieldbus Parameter	IS Entity	FISCO Gr. IIB	FISCO Gr. IIC	HPT	FNICO Gr. IIB	FNICO Gr. IIC
Max. current (mA)	80	265	120	500	320	180
Max. devices	4	13	6	25	16	9
Max. trunk length (M[a])	1900	1900	1000	1900	1900	1000
Max. spur length (M[a])	120	60	60	120	60	60
Hazard zone	0 & 1	1	1	0 & 1	2	2

[a] *Length in meters (M).*

4.0.0 FOUNDATION FIELDBUS

According to the Fieldbus foundation "Foundation Field is an integrated total architecture for information Integration—FOUNDATION field bus is an all-digital, serial, two-way communication system." It consists of H1, connecting field equipment and high-speed Ethernet (HSE 100 Mbps). The link device is an HSE device to connect one or more H1 links. It has been incorporated into international standard IEC 61158-2. These two buses are described here:

- **H1:** H1 bus based on IEC 61158-2 standard uses field devices like sensors, transmitters, and I/Os;
- **HSE:** HSE bus is an HSE bus that provides integration of high-speed controllers, subsystems via link device, data servers, and workstations.

The Foundation Fieldbus specification is based on a layered communication model as shown Fig. AVII/4.0.0-1. Foundation Fieldbus H1 consists of three layers: *physical*, *data link*, and *user application*, as shown in Fig. AVII/4.0.0-1. Layers 3–6 are missing. The use application is made up of a function block and device description and it is directly based on the communication "stack" shown.

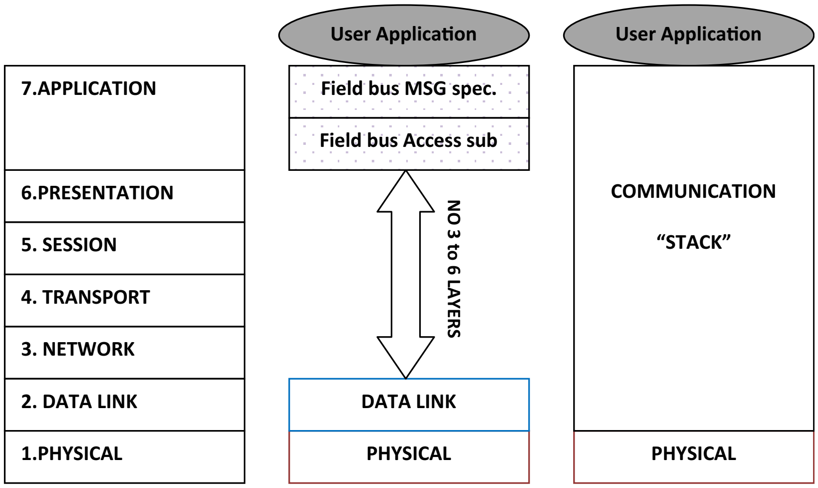


FIGURE AVII/4.0.0-1 Foundation fieldbus model.

4.1.0 Benefits of Foundation Fieldbus

Foundation Fieldbus offers the following benefits [1]:

4.1.1 BENEFITS OF H1 BUS

1. Reduced wiring, marshaling, cabinets, and equipment room size.
2. Common power supplies and IS
3. More data/multivariables from each device.
4. Distortion-free digital communication enables control capability at the field level.
5. Better performance for self-diagnostic and communication capability.
6. For distributed control at field, reduced hardware requirement.
7. Higher flexibility and sophistication.
8. More information for operation.

4.1.2 BENEFITS OF HSE BUS

The benefits discussed in the previous list are applicable to an HSE bus also. Additionally, it offers the following benefits:

1. Asset management functions like diagnostics, calibration, identification, etc., help make proactive, high-performance management actions;
2. Since the system is an open system, it is interoperable, enabling the user to mix various subsystems to form an integrated system;
3. Same functional blocks of H1 can be used here, eliminating the need for proprietary programming languages. The same language system can be used over the entire system;
4. Peer-to-peer communication enables communication between two devices without a central computer system. It is possible to bridge information between HI networks;
5. Since it is standard Ethernet, there is no need for any special tools and cables.

4.2.0 Foundation Fieldbus Technical Features and Description

The Foundation Fieldbus system has two parts, one is H1 and the other is HSE. HSE bus is basically standard Ethernet topology with a high speed of 100 Mbps for communication. Therefore, emphasis is put on the H1 bus because for HSE details standard high-speed Ethernet may be referenced and also H1 bus is more concerned with flow metering devices.

4.2.1 MAJOR TECHNICAL SPECIFICATION OF H1 BUS

Major features of H1 bus include the following:

1. **Power and IS:** Common power and IS (where applicable);
2. **Minimum voltage for communication:** 9 V;
3. **Communication speed:** 31.25 kbps;
4. **Encoding:** *Manchester encoded* data;
5. **Communication mode:** Token passing;
6. **Standard:** IEC 61158-2;
7. **Connected devices:** Sensors, flow meters, flow converters, transmitters, I/O devices.

4.2.2 TECHNICAL DESCRIPTION OF H1 BUS

H1 bus basically consists of *two* types of devices, i.e., basic unit and link master. The link master can assume responsibility for the link active scheduler discussed later (Section 4.2.3). There can be a maximum of 32 devices per H1 bus in line, tree, or star topology. The maximum number of units in hazardous units is reduced on account of the power supply limitation ($\ll$32). When a number of devices is connected to a common junction box they form a *chicken foot* as typically shown in Fig. AVII/4.2.2-1.

A daisy chain is allowed, but mostly devices including the link master are connected through a junction box (JB). The connection between devices to the JB is called the ***spur*** whereas the JB to JB connection is termed a ***trunk.*** The maximum length of the H1 bus (sum of trunk and spur) is *1900 m* without a repeater and a maximum possible spur length of 120 m. The maximum possible H1 bus distance is *9500 m.* Shielded twisted pair cables are with one end grounded and both ends terminated through resistance, as shown in Fig. AVII/4.2.2-2. Instead of a direct bulk power

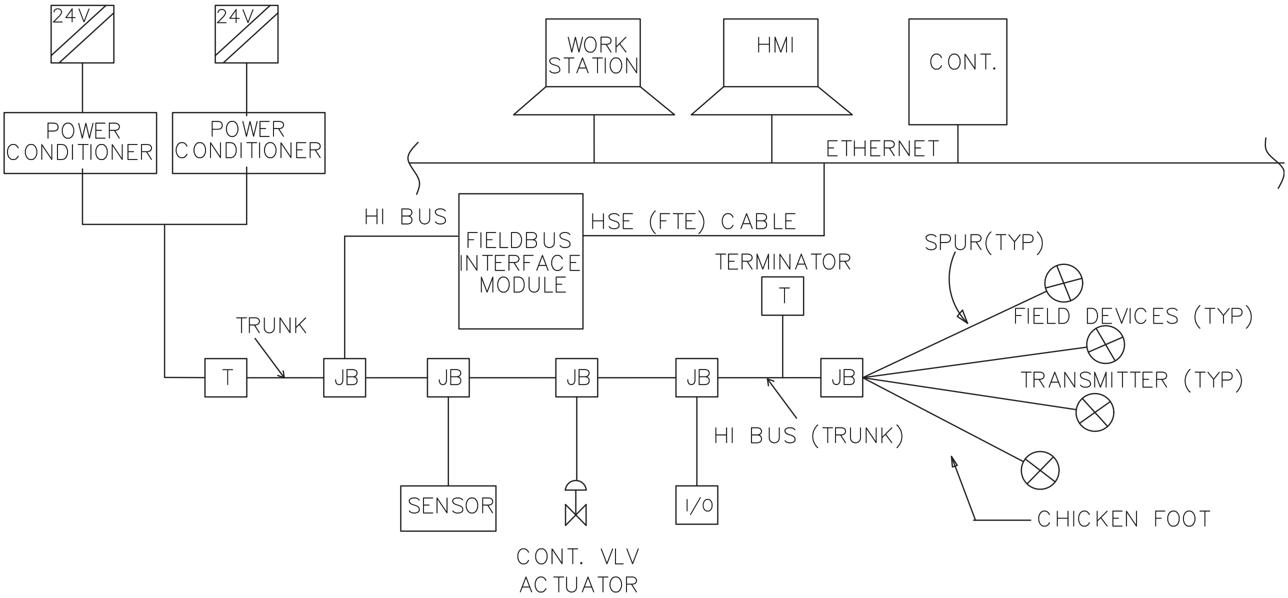
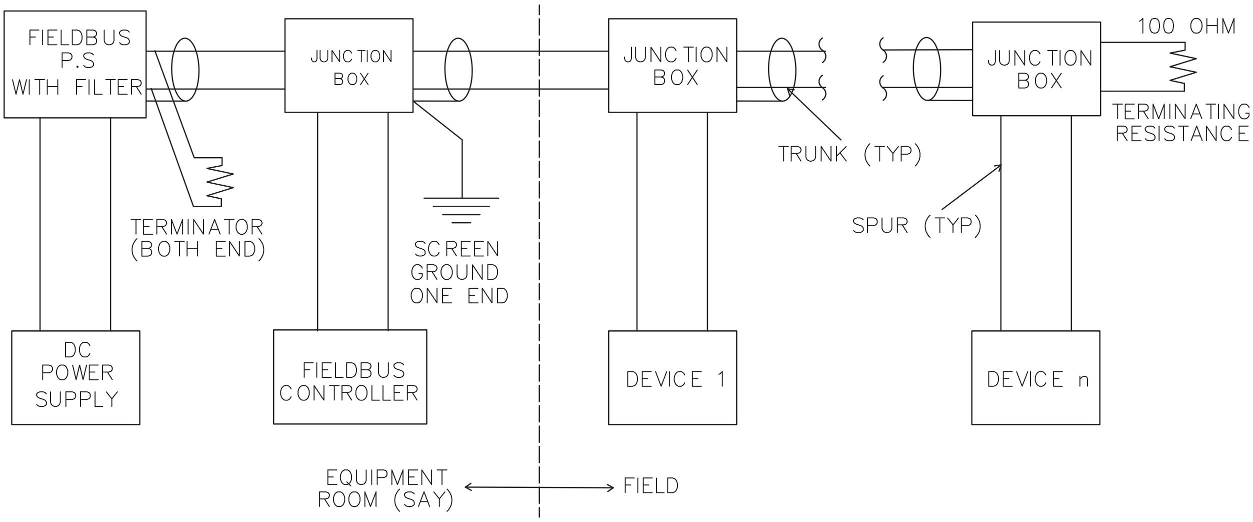


FIGURE AVII/4.2.2-1 Foundation fieldbus H1—HSE arrangement.



SPUR LENGTH TABLE (LENGTH IN METER)

NO OF DEVICES	1 DEVICE/SPUR	2 DEVICE/SPUR	3 DEVICE/SPUR	4 DEVICE/SPUR
1–12	120	90	60	30
13–14	90	60	30	1
15–18	60	30	1	1
19–24	30	1	1	1
25–32(MAX)	1	1	1	1

PREFERRED CABLE FOR FOUNDATION FIELD BUS: SHIELDED TWISTED PIAIR AWG 18 (0.8mm2)

FIGURE AVII/4.2.2-2 Foundation fieldbus cabling details.

supply connection, it is connected through a power conditioner as shown in Fig. AVII/4.2.2-1.

4.2.3 LINK DEVICE, GATEWAY AND COMMUNICATION STACK (LINK ACTIVE SCHEDULER)

A few pertinent devices for foundation fieldbus have been enumerated below.

Linking device: Like the gateway for Field device access (FDA), Field message specification (FMS), and System management (SM) services to the H1 bus, it connects one or more H1 bus to the HSE device/network. There is a difference in speed between the H1 bus and HSE bus. Conversion of data transfer rate and telegram needs are done at this device.

Gateway: As the name suggests, it is used to link the Foundation fieldbus to the interface with other standard bus systems like *Device Net, PROFIBUS, etc.* So it is used for non-HSE devices communication with the HSE network.

Communication stack: Link active scheduler: In the H1 bus a few services listed below are available. These are controlled by the link active scheduler (LAS) responsible for control and scheduling of communication over the bus.

- Devices in the H1 bus can exchange data one with other.
- Devices are served in definite time.
- No two devices can access the bus simultaneously.
- Token management for Scheduled communication (SC) and Un Scheduled communication (USC). The latter is executed in break time between SCs.

There can be more than one link master in a network and it is possible to operate the system with redundant LAS. LAS controls so many functions with the help of a series of commands it can broadcast over the bus, e.g., it broadcast the Time distribution (**TD**) signal to synchronize various operations. There are basically two kinds of communications, scheduled communication (**SC**) and unscheduled communication (**USC**). Time-critical tasks such as process controls, etc. fall under SC. On the other hand, functions like parameterization, diagnostics, etc. are unscheduled communications. These are executed in break time between two SCs. Major functions of LAS have been tabulated in Table AVII/4.2.3-1.

TABLE VII/4.2.3-1 LAS Functions

Activity	Discussions	Remarks
Scheduled communication (SC)	All time-critical tasks have strict schedule created during configuration A compel data is sent to the device. Cyclic data are sent according to a list Each device has different schedule based on its function and task	Device (e.g., a sensor) publishes specific data upon receipt of compel data and it can be received by others (e.g., CV) In SC point of time and sequence is well defined
Unscheduled communication	On request device parameters, diagnostics data are sent LAS passes token to all in the bus	Sent between break of SC LAS grants permission to access the bus when token is given to it Each device can send data till the time is expired or it finishes the data transmission.
Live list	Maintains a live list to recognize the device sending data upon token passing	
Synchronization	All devices have exactly the same time as in DLL, due to time synchronization	
Redundancy	In case of more than one link master, if LAS fails another takes over	

4.2.4 USER APPLICATION

It is based on three types of blocks to represent different application functions. These are *resource block, transducer block, and function block*. Devices are developed based on the first two blocks, whereas for control strategies function blocks are used.

1. **Resource block:** *Characteristics* of the device, such as device name, manufacturer, serial no.
2. **Transducer block:** Used to *configure* the device, read sensor, and command output value.
3. **Function block:** This is the *control strategy* builder input and output of function blocks linked over the fieldbus. There may be many function blocks in a control strategy and these are scheduled. AI, AO, DI, DO manual loader, PID, bias gain, etc. are the standard ones. *Control strategy building at the fieldbus is unique to the Foundation Fieldbus.*

Let us conclude the discussions on the Foundation Fieldbus to look into the PROFIBUS fieldbus.

5.0.0 PROFIBUS AND PROFINET

Introduced in 1989 in Germany (DIN18245), PROFIBUS is one of the most popular Fieldbus standards. It has been incorporated into international standard IEC 61158-2.

5.1.0 PROFIBUS Family and Application Area

The PROFIBUS systems consist of three compatible versions that operate together seamlessly.

1. **PROFI FMS (field message specification):** This is a high-end application-level communication. It provides object-oriented transmission with structured data, loading, and control programs. The extension of other family members such as PROFIBUS DP and its suitable integration with the Ethernet gave rise to PROFINET, which made FMS less important and less popular.
2. **PROFIBUS DP (decentralized periphery):** Low-cost field and controller level communication. The majority of PROFIBUS devices belong to this category.
3. **PROFIBUS PA (process automation):** This is a cost-effective, two-wire connection used for field devices to communicate.

TABLE VII/5.1.0-1 PROFIBUS Application [1]

Application Area	Applicable Industries
Simple to large low-cost distributed control and automation application	Factory automation, robotics
High-speed time-critical application	Process control and power industries
Complex communication tasks	Building automation, warehousing and material handling
Hazardous applications and process automation	Smart devices

For safety-critical applications, PROFIBUS has PROFISAFE, and for IT applications and networking there is PROFINET. Table AVII/5.1.0-1 gives a clear picture of the application of PROFIBUS.

5.2.0 PROFIBUS Structure

PROFIBUS has two layers: the physical and Fieldbus data link layers (FDL). All three types of PROFIBUS are nearly identical (refer to Fig. AVII/5.2.0-1). When compared with the ISO/OSI model, it is clear that layers 3–6 are missing in PROFIBUS where FDL handles transmission protocol, data security, and error detection. The original DP has been extended to include these functions, referred to as DPVs, which are found in the application layer. PROFIBUS DP and PROFIBUS PA have been

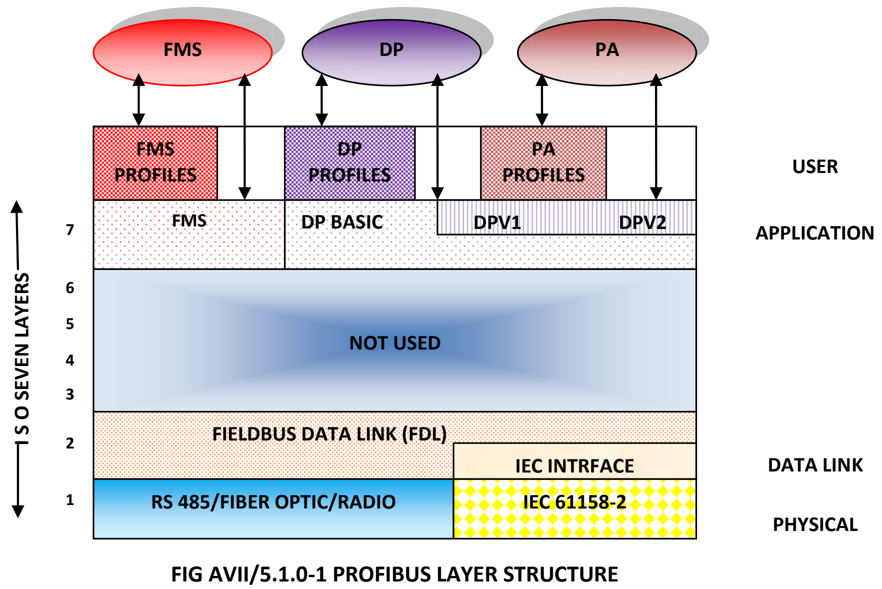


FIGURE AVII/5.2.0-1 PROFIBUS layer structure.

TABLE VII/5.2.0-1 PROFI BUS Transmission Techniques

Tr. Technique	FMS/DP	PA
RS 485	Twisted pair or with four wires with power supply speed: 9.6–1200 kbps	
Optical	High-speed communication with electrical isolation	Not applicable
IEC 61158-2	Not applicable	Shielded twisted pair cable @ 31.5 kbps. Supply and data on the same cable (IS possible)

connected through couplers. The physical medium and transmission details have been indicated in Table AVII/5.2.0-1.

Now let us look at the configuration and communication for the PROFIBUS system.

5.3.0 PROFIBUS Configuration and Communication

Typical PROFIBUS configuration and communication means have been elaborated in Fig. AVII/5.3.0-1.

This communication is based on a token passing ring type as defined in Fig. AVII/5.3.0-2.

Of 0–128 device numbering, 126 is reserved for generic devices and 127 is used for broadcast messages. But the limit from IEC 61158-2 and RS 485 is that there are only 32 per segment. Address setting means (HW and SW) are as follows:

- Hardware is by local binary dip switch or rotary switch;
- Software setting over PROFIBUS;
- Special software and serial link by hand-held device or control system.

In line with IEC 61158-2, the topology can be linear in RS 485, daisy chained connected. Alternatively topology can be tree type also. The circuits

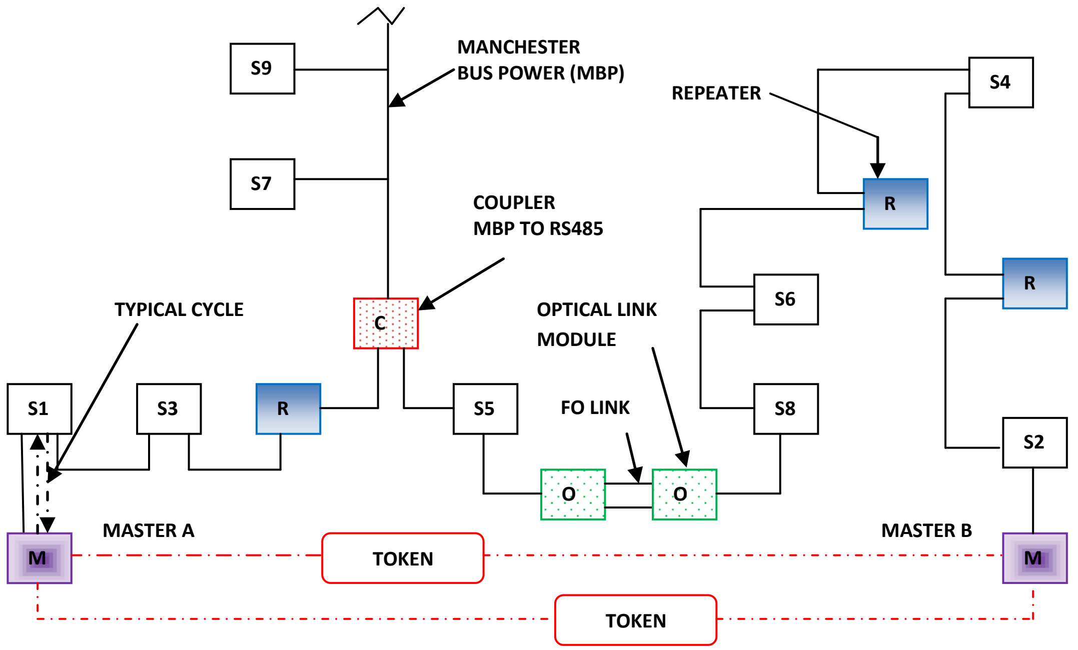


FIGURE AVII/5.3.0-1 PROFIBUS configuration and communication.

Developed by IBM in 1970, Token passing is compatible with the standard IEEE 802.5. As per standard the data rate as 4-16 Mbps and the station per segment as 250. When a station/node possessing a token wants to transmit information, it seizes the token, alters 1 bit of the token, appends information, and sends it to the next station/node. The next station/node sees and sends it to next station. In this fashion, the information circulates in the ring until it reaches the destination.

FIGURE AVII/5.3.0-2 Token passing ring communication.

can include repeaters, couplers, and optical link modules (for transforming optical signals into electrical signals) as shown in Fig. AVII/5.3.0-1. A few pertinent issues and components are as follows:

1. **Signal coupler:** The signal coupler is very important as it helps in coupling two systems. In one side is the PA in line with the IEC 61158-2 technique and the other side is RS 485. Through the signal coupler both sides can be married so that IS and signal transmissions are possible. The signal coupler has the following features:
   - Electrical isolation between safe and IS bus;
   - It is like a slave to PROFI DP;
   - Baud rate adaption (PA; 31 Kbps) is faster (1200 Kbps);
   - Powering of PA bus;

   Now let us look into PROFIBUS operation.
2. **Connection supports:** PROFIBUS supports various types of wiring, as listed below:
   - *RS 485:* The preferred connector could be a nine-pin D SUB plug for RS 485. Termination is necessary at both ends, preferably one with a master. The first and last segments can have 31 stations and the rest are restricted to 30. Wires are color-coded and the shield may be connected to the body.
   - *Optical connections:* Long-distance use of optical module including optical link module (OLM). Line, ring, and star configurations are possible.
   - *IS wiring support:* This is already covered in Section 3.2.0

5.3.1 PROFIBUS OPERATION

PROFIBUS operation is in a master–slave mode with more than one master. Master stations control the network communication and the slave responds to the call from the master. Each of the masters can communicate with a number of slaves. The system is highly democratic, meaning that all masters have equal rights, also all of the slaves connected to any master have equal rights. In the case of a multimaster system, communication is regulated by the token-passing method as shown in Fig. AVII/5.3.0-1. In multiple master systems, one master is in command. During the period a master having the token completes all communication with associated slaves. Then they pass on the token to next master. In this way communication goes on, meaning at any point in time only one master (having the token) is communicating. There are two classes of masters, Class 1 and Class 2, with functional details elaborated in Table AVII/5.3.1-1.

5.3.2 CYCLIC AND ACYCLIC COMMUNICATION

As shown in Fig. AVII/5.3.0-1, the normal communication system in DP is cyclic. A master with a token (token-holding time is calculated and specified by the user) talks to all its slaves in a cyclic manner, e.g., Master (MA) to Slave1 (S1) followed by S1 to MA then to S3 (under control of MA), etc. As stated above, after the communication is complete, it is passed on to the next master (e.g., MB) when MB does its communication and MB to S2 is followed by S2 to MB then to S4 (under control of MB), etc. Cyclic communication is transparent. When a master requires any information from a slave it simply writes it in the appropriate part of the memory of the master for the slave to retrieve. The slave puts the required information in the appropriate part of the memory of the master to be retrieved by the master. Slaves always monitor the bus, utilizing a watchdog timer to check the inactivity in the bus. If a message is not received within a specified time, it senses an error in communication and goes into a fail-safe condition. During the cyclic operation, the master checks the health of the slave, making sure that it responds to all the calls from the master. Acyclic operation is unique for DPM2 to access the network and read/write to any slave during *configuration and start-ups*.

5.3.3 NETWORKING

The PROFIBUS network needs to be configured first. During configuration, the master is notified about the basic characteristics of the slaves. This is done with the help of software supplied by the PROFIBUS master manufacturer. During configuration the token-holding time is also set. General station description (GSD) files help in

TABLE VII/5.3.1-1 Master Classification (PROFIBUS)

Functions	Class I Master	Class 2 Master
Designation	DPM1	DPM2
Processing and operation	Information processing to and from slave during normal operation	Engineering functions, such as configuration tool, diagnostic, engineering, etc. It is used for operation and monitoring purposes. It is also used during start up
Authority	One master can write to the outputs of a particular slave	Can read and write to the outputs of any slave even when it is under control of a master
Communication	It communicate with slave in *cyclic* operation due to DPV1 function of extended DP	It uses *acyclic* communication for access

such configurations. When the master device is initialized, the master (Class 1) sets the parameter into the slaves, i.e., it provides the slaves with required settings and to lock themselves to the master. This is called parameterization. Next, it is important during start-up to check the configuration by the master to confirm that the slave is configured as per the requirement set forth by the master. At the final stage, a diagnostic request is sent by the master (Class 2), which is responded to by the slave, satisfying to the master that the slave has no problems.

5.3.4 GENERAL STATION DESCRIPTIONS AND ASSOCIATED PARAMETERS

The configuration of all supporters of PROFIBUS has been standardized with the help of a set of files called general station descriptions (GSD) files. GSD files are helpful during interoperability and are loaded to the master at the planning stage for system development. Basic data supplied by GSDs include but are not limited to the following:

1. Device manufacturer and device identification number;
2. Transmission rate and bus parameter;
3. Number and format of the data cyclic communication;
4. Device profile standardizes the PROFIBUS so that all device functions and parameters are standard, and it determines the access method. There is some manufacturer-specific information, and it is accessible in a Class 2 master (if it has knowledge about them);
5. **There are two kinds of profiles**, Class A and B. These are mainly transducer blocks, which describe the coupling of signals to process characteristic curves and sensor types. The Class A profile is limited to absolutely necessary information and Class B extends this to the available scope of the function of devices;
6. **Two specifications are used to enable the Class 2 master manufacturer-specific features and operating functions**, electronic device description (EDD) and the field device tool (FDT).

5.3.5 FEATURES OF PROFIBUS SYSTEM

PROFIBUS has two major sections, i.e., PROFIBUS DP and PROFIBUS PA. The major features of them have been listed below:

1. **PROFIBUS DP:** Salient features of PROFIBUS DP are presented below:
   - Probable baud rate is 9.6/19.2/45.45/93.75/187.5 Kbps and 1.5/3.0, 6.0, 12 Mbps;
   - Device support per segment is a maximum of 32, including masters;
   - Up to 244 byte I/P and O/P per station;
   - Data can be read by controlling and Class 2 masters;
   - Alarm acknowledgment;
   - Communication is cyclic and only one master can write in a slave for safety reasons.
2. **PROFIBUS PA:** PROFIBUS PA has the following general features:
   - Transmission technology is IEC 1158-2 (2W data and power);
   - Maintenance and diagnostics from available instruments;
   - Distance <1900 m, maximum of four repeaters;
   - Manchester coding without mean value at 9 mA;
   - 126 addressable devices but up to 32 per line segment;
   - Remote DC voltage maximum of 32 V.

5.4.0 PROFINET

PROFINET can be considered as an extension of PROFIBUS DP and it can be integrated with Ethernet to develop PROFINET. The technology can be used in different manners [8]:

- As a bus system (mainly used in production automation);
- As a backbone network for heterogeneous networks with consistent basic communication (connection to different network types via a proxy server).

PROFINET, in accordance with IEC 61158 and IEC 61784, is an open industrial Ethernet. It simultaneously supports TCP/IP, Ethernet, OPC

(OPC is a tool for system integration) and XML (XML is an extensible markup language for data). In addition to PROFIBUS, it also supports other fieldbus systems through proxy technology [1]. Interested readers can refer chapter VII of latest revision of author's book [1] where detailed discussions on device communication has been presented.

I hope you have enjoyed reading this book and look forward to your feedback in the form of reviews. Any feedback, comments (good or bad), or suggestions from you would be valuable and are always welcomed.

Author

LIST OF ABBREVIATIONS

BPCS Basic process/plant control system
EAC Electrical area classification
EPL Equipment protection level
HFT Hardware failure tolerance
IS Intrinsic safety
LEL Lower explosive limit
OLM Optical link module
PFD Probability of failure on demand
SFF Safe failure fraction
SIF Safety instrumented function
SIL Safety integration level
SIS Safety instrumented system
UEL Upper explosive limit

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Plant Flow Measurement and Control Handbook

Fluid, Solid, Slurry and Multiphase Flow

Plant Flow Measurement and Control Handbook is a complete and comprehensive handbook on flow measurement and control, which covers the entire spectrum of flow measurement, such as fluid, solid, slurry, and multiphase flows. It is a valuable source of reference for practicing engineers and advanced graduate students in the fields of instrumentation, process controls, and process engineering. The book encompasses both theoretical discussions as well as practical topics such as installation, calibration testing and commissioning, custody transfer issues, as well as advanced control and communication methodologies. The book gives an overview of available techniques with recommendations for application, and covers available flow sensors-related technologies, including fiscal measurement techniques, automation, and control. The author brings his 38 years of experience in working in instrumentation and control within industry to this title.

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