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Revision Memo

12/01	General Revision. Updated references list. Added descriptions with respect to flow conditioning and custody transfer measurements.
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SCOPE

This section covers the aspects of flow measurement and control that are required for the development of a Process Design Specification. The discussions are generally limited to closed-conduit type flow meters in single-phase applications. For the meters that are covered, both theoretical and practical information is presented, in an attempt to provide a single design reference for process designers, as well as for new and practicing instrument engineers.

REFERENCES

DESIGN PRACTICES

Section X-A	Pumps - Pumping Service Design Procedures
Section XI-E	Compressors - Centrifugal Compressors
Section XIV-A	Fluid Flow - General
Section XIV-B	Fluid Flow - Single Phase Liquid Flow
Section XIV-C	Fluid Flow - Single Phase Gas Flow

GLOBAL PRACTICES

GP 3-6-1	Piping for Instruments
GP 15-4-1	Flow Instruments
GP 15-6-1	Electronic and Pneumatic Instruments

INDUSTRY PRACTICES AND PUBLICATIONS

▶ American Petroleum Institute (API), *Manual of Petroleum Measurement Standards*

Chapter 4	Proving Systems, Section 1 - Introduction
Chapter 4	Proving Systems, Section 2 - Conventional Pipe Provers
Chapter 4	Proving Systems, Section 6 - Pulse Interpolation
Chapter 5	Liquid Metering, Section 2 - Measurement of Hydrocarbons by Displacement Meters
Chapter 5	Liquid Metering, Section 3 - Measurement of Hydrocarbons by Turbine Meters
Chapter 5	Liquid Metering, Section 5 - Fidelity and Security of Flow Measurement Pulsed Data Transmission Systems
Chapter 12	Section 2 - Calculation of Petroleum Quantities Measured by Turbine or Displacement Meters
Chapter 14	Section 3 - Concentric, Square-edge Orifice Meters
Chapter 21	Section 1 - Flow Measurement Using Electronic Metering Systems

International Standards Organization (ISO)

ISO 5167	Measurement of Fluid Flow by Means of Orifice Plates, Nozzles, and Venturi Tubes Inserted in Circular Cross-section Conduits Running Full.
ISO 5168	Measurement of Fluid Flow - Estimation of Uncertainty of a Flow Rate Measurement.
▶ ISO 10790	Measurement of Fluid Flow in Closed Conduits - Guidance to the Selection, Installation and Use of Coriolis Meters.

▶ American Gas Association

▶ Report No 9	Measurement of Gas by Multipath Ultrasonic Meters
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OTHER PUBLICATIONS

Miller, R. W., *Flow Measurement Engineering Handbook*

The Foxboro Company, *Fluid Meters, Their Theory and Application*

American Society of Mechanical Engineers, *Shell Flow Meter Engineering Handbook*, Royal Dutch/Shell Group.

Dutch Shell Laboratory, *Delft Report 1312M*, Royal, Delft, Holland.

Lipták, Béla G., *Instrument Engineers Handbook*, Chilton Publishers.

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REFERENCES (Cont)

COMPANY TECHNICAL REPORTS

- ▶ EMRE 001 *EMRE Product Control Manual*
- EEEL.2E.81 *ER&E Report Information Package on Meter Proving*
- EE.13E.86 *ER&E Report Implementation Guidelines for Custody Transfer of Hydrocarbons*
- EE.46E.87 *ER&E Report Fuel Gas Flow Measurement Implementation Guide*
- EE.68E.89 *ER&E Report Implementation Guidelines for Custody Transfer of Gases*
- EE.2M.91 *ER&E Report Master Meter Proving of Positive Displacement Meters*
- ▶ HMP *Hydrocarbon Measurement Practices (HMP-Refining)*

FLOW CALCULATION PROGRAMS

- ▶ Pegasys - ExxonMobil Standard Flow Meter Analysis / Sizing Program.

Note: This program is now layered under the HSME environment and can be installed on the personal computer by approved users.

BACKGROUND

After temperature, flow is the most commonly measured variable in most refinery and chemical processes, whether the process is continuous, or batch in nature. Many processes are controlled by varying the flow of a fluid, be it reflux to a pipestill or fractionator column, heating medium to a reboiler, fuel to a fired heater, or the discharge rate from a separator. Accurate measurement and control of fluid flow is also critical from an economic point of view, since practically any fluid that flows through a plant has a price tag attached to it. In general, flow measurements can be grouped into four categories:

- Basic measurement for process monitoring and regulatory control
- Unit material balances
- Accounting information for custody transfer (product sales)
- Information required by State or Federal regulatory bodies for permitting

Control of flow is generally quite straightforward and easily accomplished, usually, the difficulty lies in selecting the proper measurement device.

FLOW MEASUREMENT

PRINCIPLES USED

There are many devices used to measure flow, many of which are inferential in nature. That is, they measure flow indirectly by measuring a related property such as a differential pressure across a flow restriction or a fluid velocity in a pipe. A number of different fundamental physical principles are used in flow measurement devices.

The most common flow measurement principle is the head meter. These devices function by converting the kinetic energy in the flowing fluid into potential energy represented by a differential pressure measured across a flow restriction in the pipe. Other devices measure the fluid velocity in a variety of ways: the generation of a counter-emf in an electric field; Doppler radar reflections off particles or bubbles in the fluid; rotation of a turbine wheel; etc. The following is a discussion of each of the various types of flow meters.

The type of flow measurement device selected depends on a large number of parameters: flowing fluid and conditions, cost, accuracy requirements, and space available, to mention the major ones. **IN ORDER TO PROPERLY DESIGN AND SIZE A FLOW METER FOR A GIVEN APPLICATION, IT IS IMPORTANT FOR THE PROCESS DESIGNER TO REALIZE THAT A MINIMUM OF PROCESS STREAM DATA MUST BE SUPPLIED AS PART OF THE PROCESS DESIGN SPECIFICATION. TABLE 1 LISTS THE MINIMUM STREAM DATA NEEDED FOR LIQUIDS, GASES (vapors), AND STEAM.**

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FLOW MEASUREMENT (Cont)

TABLE 1
FLUID PROPERTIES REQUIRED

LIQUIDS	GASES & VAPORS	STEAM
Internal Pipe ID	Internal Pipe ID	Internal Pipe ID
Operating Temperature	Operating Temperature	Operating Temperature
Operating Pressure	Operating Pressure	Operating Pressure
Viscosity	Viscosity	Viscosity (Opt)
Specific Gravity or Density	Mol. Wt. or Density	Density (Opt)
Flow Rate (Max/Nor/Min)	Flow Rate (Max/Nor/Min)	Flow Rate (Max/Nor/Min)
	Heat Capacity Ratio (Cp/Cv)	
	Compressibility	

Note: Viscosity, compressibility (gases), and specific gravity (liquids) should be specified at operating temperature and pressure.

Please note that the minimum flow rate is NOT zero flow. The minimum flow is the lowest anticipated continuous flow rate that must be measured or controlled.

For custody transfer and inventory applications, standard temperature and pressure should be stated since different countries have different standard temperature and pressure bases.

METER SELECTION CRITERIA

Although an orifice meter will most likely be selected for most applications, the proper selection of a flow meter for a particular application requires considerable evaluation of tradeoffs. It involves evaluating the total cost of ownership against many application considerations, which affect meter performance. The most important application factors, which require consideration, are fluid state, flowing conditions, Reynolds number, density, rangeability, mechanical installation constraints and accuracy requirements.

In addition to the above, the designer must also decide on what basis the measurement will be made: Mass, Volume (operating or standard) or Energy. Once known, this dictates the level of instrumentation required to produce that measurement. For example, if standard volume is selected, the meter installation, in addition to its flow meter and transmitter, will also have to be provided with field transmitters for pressure and temperature, to compensate for process variations in these variables. In some instances, a specific gravity or density analyzer may also be needed to account for variability in stream composition.

Economic considerations also come into play when selecting a meter. The initial equipment cost is not the only cost to consider. Thought should also be given to 1) total installed cost, 2) maintenance cost, and 3) operating cost. The following paragraphs discuss each of the factors required to be considered and their potential impact on the measurement. Costs must be carefully evaluated, particularly as meter size or operating pressure changes. For instance, a small sized venturi might be of comparable cost to an averaging pitot, but as the size increases the cost of the venturi rapidly exceeds that of the averaging pitot for a given pipe size. Increasing design pressure has the same effect.

Accuracy

Flow meter accuracy is defined as the closeness of agreement between the measured flow rate and the actual flow rate in a pipe. Accuracy can be considered to be made up of two components: precision and bias error. Precision is the metering device's ability to give the same flow readings for the same true value of flow. Precision is normally a function of the repeatability and stability of the system. Bias error is the difference (or offset) in the average flow value and the actual flow value. Bias error is usually caused by progressive aging and drift in the installed equipment.

Plant applications can be classified into three categories:

- Class I Sales, Custody Transfer, and other applications requiring high accuracy
- Class II Material Balance, and Equipment Performance applications
- Class III General Purpose

The system accuracy achievable for typical meter types, as defined by EMRE 001 *Product Control Manual*, for each of the above Classes is shown in **Table 2**.

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FLOW MEASUREMENT (Cont)

TABLE 2
BEST ACHIEVABLE ACCURACY FOR GIVEN METER INSTALLATIONS

METER TYPE	% UNCERTAINTY OF MEASURED VOLUMETRIC FLOW RATE		
	CLASS I	CLASS II	CLASS III
Positive Displacement	0.2	0.2	0.5
Turbine	0.2	0.2	—
Orifice(1)	1.0(2)	2.0	5.0
Vortex Shedding	Not recommended	0.75	1.5
Coriolis(3)	0.2	0.2	0.5
Ultrasonic (4)	Not recommended	1.0	1.4

Notes:

- (1) Uncertainty of orifice meter is listed as "% of full scale".
- (2) HMP allows orifice meters to be used in Class I applications for steam and gases only.
- (3) Uncertainty of coriolis meter is listed as "% of mass flow rate".
- (4) Multipath Ultrasonic meters only.

Rangeability

Rangeability is a flow meter's ability to cover a range of flow rates within specified accuracy limits. It is usually defined as the ratio of the maximum to minimum flow rates and is also known as meter turndown.

For differential pressure type flow meters, because of the square root relationship between flow rate and differential pressure, flow rangeability is usually severely limited without taking certain measures. As shown in **Figure 1**, for a change in differential pressure from 100% down to 10% of full scale (about the limit for reasonable accuracy with conventional transmitters), the change in flow rate is only from 100% to 30% of full scale. Therefore, in most differential pressure applications, the maximum usable rangeability of an orifice is about 100/30 or roughly 3 to 1 with a standard differential pressure transmitter. **GP 15-4-1** states "The normal flow rate should be between 70% to 80% of the full scale flow provided that the anticipated minimum and maximum flow rates will be between 30% and 95% of the full scale flow". This limits the working rangeability to 950/30, or roughly 3 to 1. However, in certain cases, this rangeability may be extended up to 10 to 1 through the use of the new, high-accuracy, digital differential pressure transmitter, that have an accuracy better than 0.1% of the calibrated range provided that the minimum dP is greater than 0.1in. of water (25.4 mm of water).

The reason for this is the calibrated range of the transmitter corresponding to the measured differential pressure at the minimum flow rate gets so small (less than 1 in. of water), the transmitter is unable to accurately distinguish between a true differential pressure change due to flow, versus pure process background noise in the pipe.

If greater than 4 to 1 rangeability is required using conventional transmitters, multiple differential pressure transmitters may be installed in parallel across the same set of orifice taps. In this approach, each transmitter provides for a 3 to 1 rangeability and is designed to measure a specific flow range. Switching logic is then utilized in the process control system to select the correct transmitter. In most modern control systems, this switch is automatic. So, for example, if an orifice is supplied with two differential pressure transmitters, this equates to a rangeability of 9 to 1. In the practical sense, no more than 3 conventional d/p transmitters should be installed in parallel across an orifice plate. It should be noted that for multiple transmitters on one orifice plate, the pressure drop at the highest expected flow rate should be taken into account in hydraulic balances.

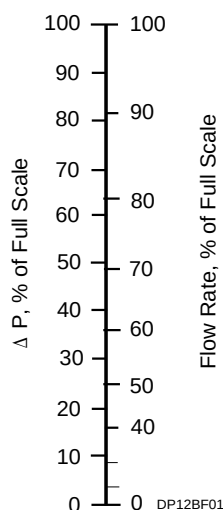
If high accuracy digital transmitters are used, three transmitters on the same set of taps would provide 1000:1 rangeability, adequate for any foreseeable application. **CAUTION: In these wide rangeability applications, the pipe Reynolds Number should be calculated at the lowest flow rate to be measured to verify turbulent flow conditions still exist.**

For non-head type flow meters, the above problem with the square root relationship between flow rate and differential pressure does not exist. Non-head type flow meters can generally provide wider rangeability, usually on the order of 10:1. When greater than 10:1 is needed, parallel meter runs are usually employed.

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FLOW MEASUREMENT (Cont)

FIGURE 1
COMPARISON OF DP AND FLOW RATE FOR DIFFERENTIAL PRESSURE FLOW ELEMENT



Discharge Coefficient (C)

Every head type flow meter geometry has something called a discharge coefficient, (C). The discharge coefficient corrects the theoretical flow rate equation for the influence of velocity profile (Reynolds number). Specific discharge coefficients for various flow meter geometries have been determined by actual tests run by many different organizations (e.g., API, ASME) over the past 75 years. The discharge coefficient is a very important factor in defining the shape of the flow path. It is heavily influenced by factors such as: the size of the orifice bore, the size of the pipe, fluid velocity, fluid density, and fluid viscosity.

The orifice to pipe diameter ratio, d/D , also called (beta ratio- β) in flow meter literature, is usually limited to a maximum of 0.7, because of the sensitivity of the discharge coefficient to such things as pipe diameter variation and wall roughness. However, for new designs it is best to limit β to 0.65. If the d/D ratio limit is exceeded, it can be reduced by increasing line size for the length of the meter run. A high d/D ratio is a sign of unusually high line velocity and the piping pressure drop calculations should be checked. On the opposite end, β is usually limited to a minimum of 0.25. Anything less than 0.25 would be suspicious, indicating oversized pipe; as the area of a 0.25 d/D orifice would be only 6 percent of the pipe area. Hence, for new meter designs, the beta ratio should be kept in the range of 0.25 to 0.70.

Reynolds Number

Reynolds number is a dimensionless number expressing the ratio of the dynamic forces to the drag forces of a fluid. Reynolds number is used as a way to correlate the variations in flow meter coefficient of discharge (C) with changes in the fluid's properties, flow rate, and meter geometry. In its simple form (from **API Chapter 14**, Section 3, Part 1), the Reynolds number can be expressed as:

$$R_e = \frac{N_2 q_m}{\mu D}$$

where: R_e = Pipe Reynolds number (dimensionless)
 N_2 = Unit Conversion Constant
 q_m = Mass Flow Rate
 μ = Absolute Viscosity of the fluid
 D = Meter Tube Inside Diameter

	UNITS	
	Customary	Metric
	1.27324	353.6777
	lb _m /s	kg/hr
	lb _m /ft/s	cP
	ft	mm



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FLOW MEASUREMENT (Cont)

Reynolds number can be expressed in two ways: Pipe Reynolds number or Throat Reynolds number. Do not confuse them, as they are not interchangeable. Pipe Reynolds number will always be lower than the throat Reynolds number. However, pipe Reynolds number is more convenient to use because in most cases, at the time of design, the orifice throat dimension is not usually known. Pipe Reynolds number does not represent the true performance of a flow element. It is for this reason that, whenever possible, a throat Reynolds number should be calculated.

At low Reynolds numbers, the drag (viscous) forces dominate and flow is said to be laminar in nature (see **Figure 2**). As Reynolds number increases, the drag forces become less dominant and the flow is said to be turbulent in nature (see **Figure 3**). In order for most differential flow applications to provide reasonable results, the flow profile in the pipe should be turbulent or in a range where the pipe Reynolds number is 10,000 or greater. This assures operation over the flat or constant portion of a differential device's discharge coefficient (C) curve, and away from the sloped portion of the curve. See **Figure 4**.

FIGURE 2
LAMINAR FLOW PROFILE

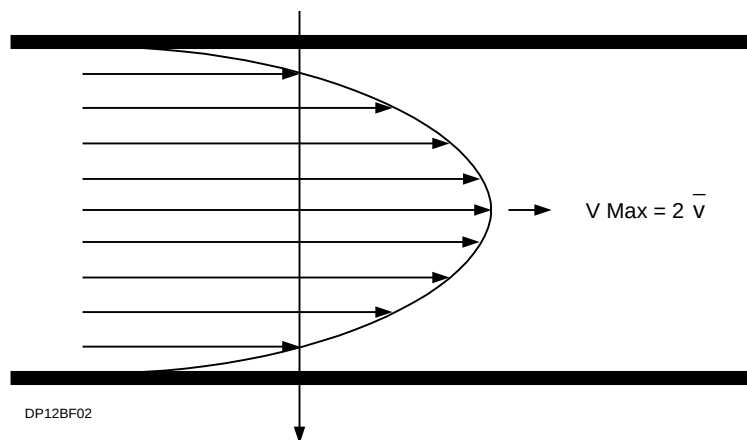
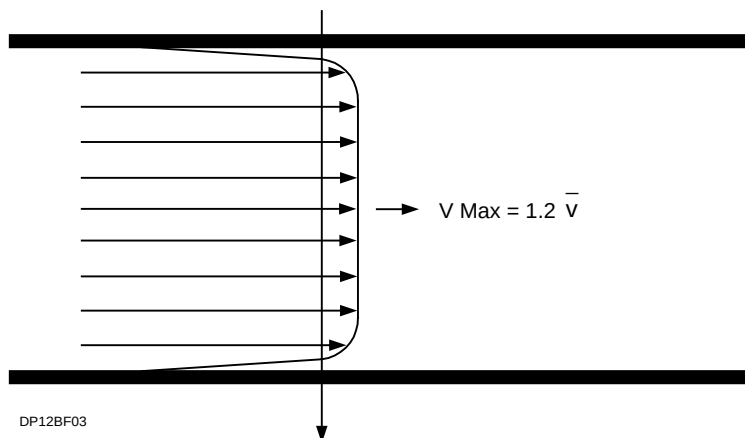
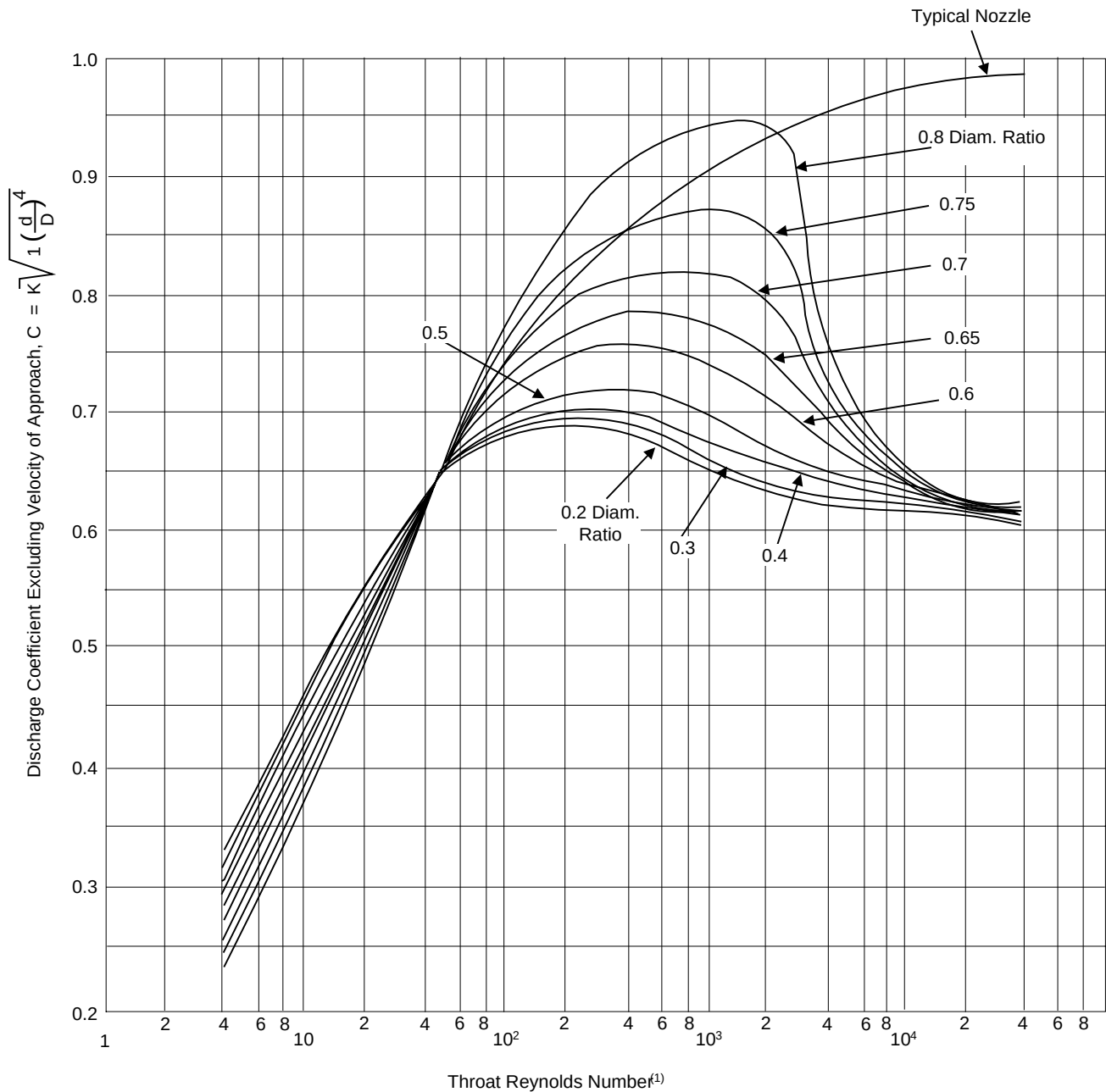


FIGURE 3
TURBULENT FLOW PROFILE



FLOW MEASUREMENT (Cont)

FIGURE 4
DISCHARGE COEFFICIENTS FOR ORIFICES AND NOZZLES IN VISCOUS SERVICE WITH FLANGE TAPS

**Note:**

- (1) This chart is based on R_d , the Reynolds number computed from throat diameter and velocity, all other references in this subsection are to R_D , the Reynolds number computed from pipe diameter and velocity.

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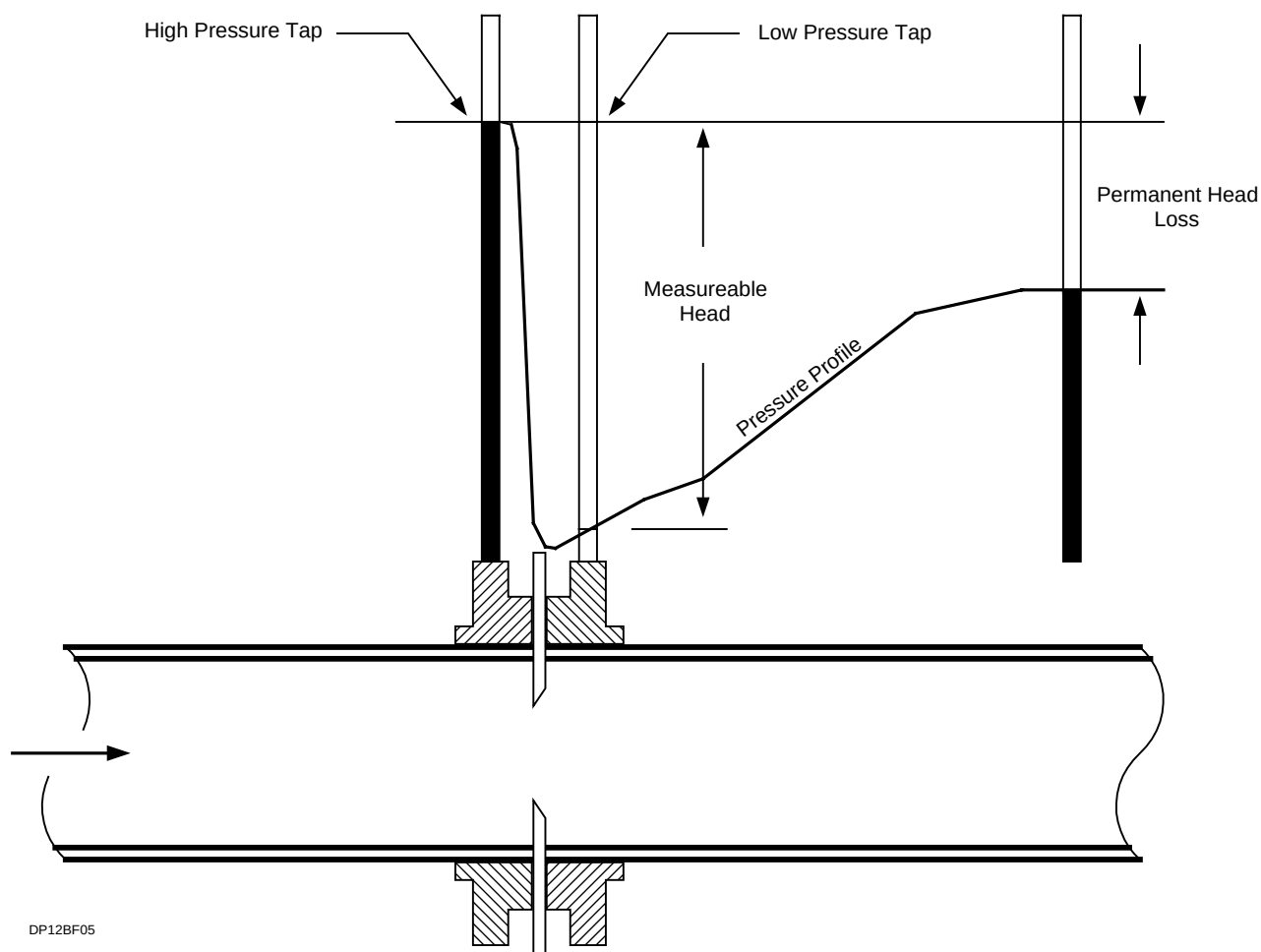
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FLOW MEASUREMENT (Cont)

Pressure Drop

Pressure drop is a reflection of the energy lost when a fluid is passed through a flow meter. In most applications, pressure drop is a heavily weighted factor during the meter selection process due to energy costs. As shown in **Figure 5**, as fluid passes through a flow restriction in a pipe, the upstream static pressure decreases sharply and then recovers somewhat downstream of the restriction. This difference between the upstream static pressure and the final downstream static pressure is called the pressure drop or permanent (unrecoverable) pressure loss. **Figure 6** shows the estimated permanent pressure loss for various differential pressure type flow meters.

**FIGURE 5
UNRECOVERABLE PRESSURE LOSS**



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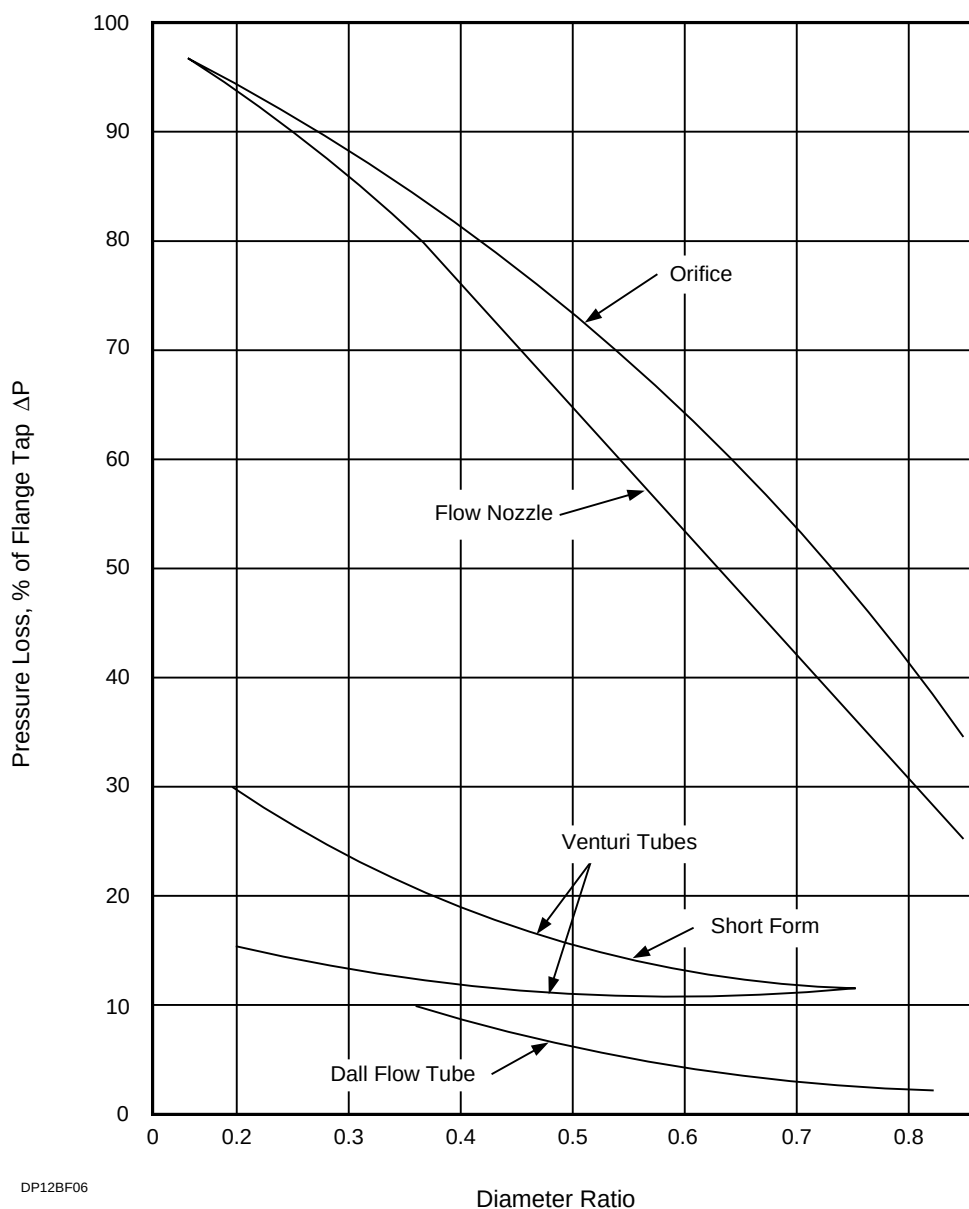
During design, the unrecoverable pressure loss for differential type flow meters can usually be calculated as a percentage of the differential meter range selected. Historically, in refining and chemicals, standard meter differential ranges of 10, 20, 25, 50, 100, and 200 in. of water, (25, 50, 62.5, 125, 250, 500 mbar) are used. For specified flow rates, this resulted in non-standard orifice bore sizes which had to be bored to tolerances of 0.001 in. (0.025 mm). With today's calibration technology, the use of standard orifice sizes - typically increments of 0.25 or 0.125 in. (6 - 12 mm) - can be considered to facilitate ordering and stocking orifice plates. For new designs, a preliminary meter range of 100 in. (125 mbar) is preferred. This represents a good compromise between a sufficient differential pressure for accuracy and permanent pressure loss. For example, for most orifice plates, the permanent pressure loss is usually around 60 percent of the meter range. For a 100 in. (250 mbar) of water meter range, this equates approximately to 60 in. of water (150 mbar) or 2.0 psi (0.15 bar). Again, the normal flow rate (70 - 80% of full scale flow rate) will occur at 50 - 60% of these full scale pressure differentials.

FLOW MEASUREMENT (Cont)

Because the density of compressible fluids changes as it flows through the flow element, an "expansion factor (Y)" or density correction is normally included. For maximum accuracy, this change in density should be limited to 1.0 percent, when determining Y from an upstream static pressure measurement. This can be achieved by keeping the differential meter range to less than 1/40th of the upstream line pressure (absolute). In cases where it is known that the downstream static pressure is used in the flow calculation, the differential meter range should be less than 1/15th of the downstream line pressure (absolute) to achieve the same 1.0 percent density change limit, since the Y curves show a given change in differential pressure causes less variation in the value of Y² under these conditions. Regardless of which location is used to determine the expansion factor (Y), the selected meter range in inches of water (mm) should not exceed 1.5 times the upstream static pressure value in psia (bara).

If the minimum pressure of a liquid flowing through the differential producing device is below the bubble point of the liquid, flashing will cause multi-phase flow, resulting in severe loss of measurement accuracy.

FIGURE 6
OVERALL PERMANENT PRESSURE LOSS THROUGH VARIOUS PRIMARY ELEMENTS



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