INSTRUMENT ENGINEERS' HANDBOOK

Fourth Edition

Process Measurement and Analysis

BÉLA G. LIPTÁK, Editor-in-Chief

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Flow Measurement

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2.1 Application and Selection

D. J. LOMAS (1982) **B. G. LIPTÁK** (1995, 2003)

No industrial measurement is more important than the accurate detection of the flow rates of gases, liquids, and solids. In this section, an overview is given of the availability and characteristics of some of the most widely used flow sensors. In addition, emphasis is given to the latest developments, such as the polyphase (oil/water/gas) and the wide-rangeability dual-rotor turbine flowmeters. General guidelines are provided about selecting the best flow sensor for a particular application.

GETTING ORIENTED

Table 2.1a provides information on conversion factors among flow measurement units, whereas Table 2.1b summarizes the features and capabilities of more than 20 flow sensor families. The variety of choices that an application engineer faces is even greater, because nearly every flowmeter category can be further subdivided into a variety of distinctly different subcategories. For example, the positive-displacement type of flow sensors include rotary piston, oval gear, sliding vane, and reciprocating piston designs. If these subvariants are also counted, the number of flow sensors available for consideration is even higher.

The selection process should consist of at least two steps. First, identify the meters that are technically capable of performing the required measurement and are available in the required size and materials of construction. Once such a list has been developed, proceed to consider cost, delivery, performance, and other factors to arrive at the best selection.

When considering a particular application, we might use a yellow marker on a copy of Table 2.1b to highlight the nature of the process fluid, the purpose of the measurement, and the displays or transmission signals required. By this process, we are likely to eliminate from consideration about half of the flow sensors listed in the table.

After this first pass, concentrate on the performance requirements, such as the maximum error that can be tolerated (defined either as a percentage of actual reading or full scale) and the required metering range. Based on the error limits and range requirements, we can next determine the rangeability required for the particular application (the ratio of maximum and minimum flow limits within which the

TABLE 2.1a
Conversion of Volume or Flow Units

To Convert	Into	Multiply by
cubic feet	bushels (dry)	0.8036
cubic feet	cu. cm	28,320.0
cubic feet	cu. in.	1,728.0
cubic feet	cu. meters	0.02832
cubic feet	cu. yards	0.03704
cubic feet	gallons (U.S. liq.)	7.48052
cubic feet	liters	28.32
cubic feet	pints (U.S. liq.)	59.84
cubic feet	quarts (U.S. liq.)	29.92
cubic feet/min	cu. cm/sec	472.0
cubic feet/min	gallons/sec	0.1247
cubic feet/min	liters/sec	0.4720
cubic feet/min	pounds of water/min	62.43
cubic feet/sec	million gals/day	0.646317
cubic feet/sec	gallons/min	448.831
cubic meters	cu. Ft	35.31
cubic meters	cu. in.	61,023.0
cubic meters	cu. yards	1.308
cubic meters	gallons (U.S. liq.)	264.2
cubic meters	liters	1,000.0
cubic meters	pints (U.S. liq.)	2,113.0
cubic meters	quarts (U.S. liq.)	1,057.0
gallons	cu. cm	3,785.0
gallons	cu. ft	0.1337
gallons	cu. in.	231.0
gallons	cu. meters	3.785×10^{-3}
gallons	cu. yards	4.951×10^{-3}
gallons	liters	3.785
gallons (liq. Br. Imp.)	gallons (U.S. liq.)	1.20095
gallons (U.S.)	gallons (Imp.)	0.83267
gallons of water	pounds of water	8.3453
gallons/min	cu. ft/sec	2.228×10^{-3}
gallons/min	liters/sec	0.06308

TABLE 2.1a Continued
Conversion of Volume or Flow Units

To Convert	Into	Multiply by
gallons/min	cu. ft/hr	8.0208
kilograms	dynes	980,665.0
kilograms	grams	1,000.0
kilograms	poundals	70.93
kilograms	pounds	2.205
kilograms	tons (long)	9.842×10^{-4}
kilograms	tons (short)	1.102×10^{-3}
pounds	drams	256.0
pounds	dynes	44.4823×10^{4}
pounds	grains	7,000.0
pounds	grams	453.5924
pounds	kilograms	0.4536
pounds	ounces	16.0
pounds	ounces (troy)	14.5833
pounds	poundals	32.17
pounds	pounds (troy)	1.21528
pounds	tons (short)	0.0005

specified error limit must not be exceeded) and identify the flow sensor categories that can provide such rangeability.

After considering such key criteria as rangeability, it is appropriate to prepare a list of other requirements that might relate to installation, operation, or maintenance and, by referring to Tables 2.1b through 2.1e, check their availability. Usually, by the end of this process, the choice will have been narrowed to two or three designs.

Having narrowed the choices, the application engineer is advised to turn the pages of this handbook to the sections in which the selected flowmeter designs are discussed. At the beginning of each of these sections, a "feature summary" is provided, containing data on the limits on operating pressure and temperature, sizes, construction materials, costs, and other factors. The final selection is usually made by choosing the least expensive flow sensor that possesses all the features and characteristics needed for the application.

Special Requirements

To consider such special features as reverse flow, pulsating flow, response time, and so on, it is necessary to study the individual meter specifications in detail. Sometimes it is also necessary to obtain unpublished test data from the manufacturers.

Although the steps we have described will eliminate the technically unsuitable meters, it does not necessarily follow that a meter will always be found that is perfectly suited for a given application. For example, electromagnetic flowmeters are available for operating at pressures as high as 1500 PSIG (10.3×106 N/m^2). They are also available for flow rates as high as 500,000 GPM (31.5 m^3/sec), but they are not available to detect a flow rate of 500,000 GPM at 1500 PSIG.

The list of technically suitable meters will get shorter as the complexity of the application increases. For an application in which the flow of a highly corrosive and nonconductive sludge is to be measured, the list of acceptable sensors might consist of a single meter design (the cross-correlation type discussed later in this section). In contrast, on a straightforward clean-water application, the list will consist of most of the flow detectors listed in the orientation table (Table 2.1b).

In such cases, the engineer should narrow the choice by concentrating on the reasons for measuring the flow. We should ask if high accuracy is the most important or if the emphasis should be on long-term repeatability, low installed cost, or ease of maintenance. It should also be realized that certain flow detectors, such as those for the measurement of two-phase flow, are still in the developmental stage and are not readily available.[1–4]

In the following paragraphs, the features, characteristics, and limitations of some of the more widely used flow sensor categories will be briefly discussed. After that discussion, the important considerations of cost, accuracy, Reynolds number, safety, and installation requirements will be covered.

DIFFERENTIAL PRESSURE

The detection of pressure drop across a restriction is undoubtedly the most widely used method of industrial flow measurement. The pressure decrease that results from a flowing stream passing through a restriction is proportional to the flow rate and to fluid density. Therefore, if the density is constant (or if it is measured and we correct for its variations), the pressure drop can be interpreted into a reading of flow. This relationship is described by the following formula:

$$Q(\text{flow}) = K(\text{constant})\sqrt{\frac{h(\text{differential head})}{d(\text{fluid density})}} \qquad \mathbf{2.1(1)}$$

Differential-pressure (d/p) meters have the advantage of being the most familiar meter type. They are widely used to measure the flow of both gases and liquids, including viscous and corrosive fluids. Their advantages include the lack of moving parts and a suitability for practically all flow rates in a wide variety of pipes and tubes.

All differential-pressure meters exhibit a square-law relationship between the generated head and flow rate, which severely limits their rangeability (typically 3:1, with 4:1 being the maximum). Another disadvantage of d/p type flowmeters is that, in addition to the sensor element, several other components are needed to make a measurement. These include not only the readout or transmitter but also a three-valve manifold and fittings to attach the readout or transmitter

TABLE 2.1b
Orientation Table for Selecting the Right Flow Sensors

Type of Design	Applicable to Detect the Flow of: Clean Liquids	Viscous Liquids	Slurry	Gas	Solids	Direct Mass–Flow Sensor	Volumetric Flow Detector	Flow Rate Sensor	Inherent Totalizer	Direct Indicator	Transmitter Available	Linear Output	Rangeability	Pressure Loss Thru Sensor	Approx. Straight Pipe-Run requirement Upstream Diam./Downstream Diam.)	Accuracy * ± % Full Scale ** ± % Rate *** ± % Registration	FLOW RANGE Solids Flow Units: 0.1, 1.0, 10, 10^2, 10^3, 10^4 kgm/hr; 0.1, 1.0, 10, 10^2, 10^3, 10^4, 10^5, 10^6 lbm/hr Gas Flow Units: 0.05, 03, 2.8, 28.3 cc/min; 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 0.1, 1.0, 10, 10^2, 10^3, 10^4 Sm³/hr or Am³/hr; 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 0.1, 1.0, 10, 10^2, 10^3, 10^4, 10^5 SCFM or ACFM Liquid Flow Units: .004, 0.04, 0.4, 3.8, 38, 379 cc/min; 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 0.1, 1.0, 10, 10^2, 10^3, 10^4 m³/hr; 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 0.1, 1.0, 10, 10^2, 10^3, 10^4, 10^5, 10^6 gpm
Elbow Taps	✓	L	L	✓			✓	✓			✓	SR	3:1⑨	N	⑦25/10	5–10*	gpm—m³/hr SCFM—Sm³/hr
Jet Deflection				✓			✓	✓			✓	✓	25:1	N	⑦20/5	2*	SCFM—Sm³/hr
Laminar Flowmeters	✓	✓		✓			✓	✓			✓	✓	10:1	H	15/5	1/2–5*⑧	gpm—m³/hr SCFM—Sm³/hr
Magnetic Flowmeters	✓⑤	✓⑤	✓⑤				✓	✓			✓	✓	10:1⑨	H	5/3	1/2**–2*	gpm—m³/hr
Mass Flowmeters, Misc.	✓	✓	✓	✓		✓	✓	✓	SD	SD	✓	✓	100:1	A	N	1/2**	lbm/hr–kgm/hr
Coriolis	✓	✓	L	✓	SD	✓	✓	✓	SD	SD	✓	✓	20:1	H	N	0.15–1/2**	SCFM—Sm³/hr
Metering Pumps	✓	✓	✓				✓		✓		SD	✓	20:1	–	N	1/10–1*	gpm—m³/hr
Orifice (Plate or Integral Cell)	✓	L	L	✓			✓	✓			✓	SR	3:1⑨	H	⑦20/5	1/2**–2*	gpm—m³/hr SCFM—Sm³/hr
Pitot Tubes	✓		L	✓			✓	✓			✓	SR	3:1⑨	M	⑦30/5	0.5–5*	gpm—m³/hr SCFM—Sm³/hr
Positive Displacement Gas Meters				✓			✓		✓	✓	SD	✓	10:1 to 200:1	M	N	1/2–1***	SCFM—Sm³/hr

Positive Displacement Liquid Meters	✓	✓					✓		✓	✓	SD	✓	10:1⑨	H	N	0.1–2**	gpm—m^3/hr
Segmental Wedge	✓	✓	✓				✓	✓			✓	SR	3:1	M	15/5	3**	gpm—m^3/hr
Solids Flowmeters		SD	SD		✓	SD	SD	✓	✓	SD	✓	✓	20:1	—	5/3	1/2**–4*	lbm/hr–kgm/hr
Target Meters	✓	✓	L	✓			✓	✓		SD	✓	SR	4:1	H	20/5	0.5*–5*	gpm—m^3/hr SCFM—Sm^3/hr
Thermal Meters (Mass Flow)	✓	L	L	✓		✓		✓			✓	L	20:1⑨	A	5/3	1–2*	gpm—m^3/hr SCFM—Sm^3/hr
Turbine Flowmeters (Dual Turbine)	✓	L		SD			✓	✓			✓	✓	10:1 (>100:1)	H	15/5⑦	1/4**	gpm—m^3/hr SCFM—Sm^3/hr
V-Cone Flowmeter	✓	L	L	✓			✓	✓			✓	SR	3:1②	M	2/5	1/2–2**	gpm—m^3/hr ACFM—Sm^3/hr
Ultrasonic Flowmeters																	
Transit		L					✓	✓			✓	✓	20:1	N	⑦15/5	1**–2*	gpm—m^3/hr③
Doppler	✓	L	✓	L	L		✓	✓			✓	✓	10:1	N	⑦15/5	2–3*	SCFM—Sm^3/hr
Variable–Area Flowmeters (Dual float)	✓	L	L	✓			✓	✓		✓	✓	✓	5:1 (to 20:1)	A	N	1/2*–10**	gpm—m^3/hr SCFM—Sm^3/hr
Venturi Tubes	✓	L	L	✓			✓	✓			✓	SR	3:1②	M	⑦15/5	1/2**–1*	gpm—m^3/hr③
Flow Nozzles			L	✓			✓	✓			✓	SR	3:1②	H	⑦20/5	1**–2*	SCFM—Sm^3/hr
Vortex Shedding	✓			✓			✓	✓			✓	✓	10:1⑧	H	20/5	0.5–1.5**	gpm—m^3/hr
Fluidic	✓						✓	✓			✓	✓	20:1⑧	H	20/5	1–2**	ACFM—Sm^3/hr
Oscillating	✓						✓	✓			✓	✓	10:1⑧	H	20/5	0–5*	
Weirs, Flumes	✓	L	L				✓	✓			✓	SD	100:1	M	See Text	2–5*	gpm—m^3/hr③

----- = Non-standard Range
L = Limited
SD = Some Designs
H = High
A = Average
M = Minimal
N = None
SR = Square Root
① = The data in this column is for general guidance only.
② = Inherent rangeability of primary device is substantially greater than shown. Value used reflects limitation of differential pressure sensing device, when 1% of actual flow of accuracy is desired. With multiple-range intelligent transmitters the rangeability can reach 10:1.
③ = Pipe size establishes the upper limit.
④ = Practically unlimited with the probe type design.
⑤ = Must be conductive.
⑥ = Can be re-ranged over 100:1.
⑦ = Varies with upstream disturbance.
⑧ = Can be more at high Re. No. services.
⑨ = Up to 100:1 with high-precision design.
⑩ = Commercially available gas flow elements can be 1% of rate.
⑪ = More for gas turbine meters.

TABLE 2.1c
Flowmeter Selection for Metering a Variety of Fluids

	Fluid Details \ Meter Type	*Correlation*	*Elbow Taps*	*Laminar*	*Electro-Magnetic*	*Angular Momentum*	*Metering Pumps*	*Orifice*	*Pitot*	*Gas Displacement*	*Liquid Displacement*	*Solids Flowmeter*	*Target*	*Thermal*	*Liquid Turbine*	*Gas Turbine*	*Doppler U-Sonic*	*Transit U-Sonic*	*V.A.*	*Venturi*	*Vortex Shedding*	*Vortex Precession*	*Fluidic Oscillation*
Liquid	Clean	X	✓	✓	*✓	✓	✓	✓	✓	X	✓	X	✓	✓	✓	X	X	✓	✓	✓	✓	X	✓
Liquid	Dirty	✓	?	✓	*✓	✓	✓	?	?	X	X	?	✓	✓	?	X	✓	?	✓	✓	?	X	?
Liquid	Slurries	✓	X	?	*✓	?	✓	X	X	X	X	SD	?	?	X	X	?	X	X	?	X	X	X
Liquid	Low Viscosity	✓	✓	✓	*✓	✓	✓	✓	✓	X	?	X	✓	✓	✓	X	✓	✓	✓	✓	✓	X	✓
Liquid	High Viscosity	✓	?	?	*✓	?	✓	?	X	X	✓	SD	?	?	X	X	?	?	?	?	X	X	X
Liquid	Corrosive	✓	✓	?	*✓	✓	?	✓	✓	X	?	X	?	?	?	X	✓	✓	✓	?	?	X	?
Liquid	Very Corrosive	✓	?	X	*✓	X	X	?	?	X	X	X	X	?	X	X	✓	✓	✓	X	X	X	X
Gas	Low Pressure	X	✓	✓	X	✓	X	✓	✓	✓	X	X	✓	✓	X	✓	X	X	✓	✓	✓	✓	X
Gas	High Pressure	X	✓	✓	X	✓	X	✓	✓	✓	X	X	✓	✓	X	✓	X	X	X	✓	✓	✓	X
	Steam	X	X	?	X	X	X	✓	X	X	X	X	✓	X	X	SD	X	X	✓	✓	SD	X	X
	Reverse Flow	X	✓	X	✓	X	X	SD	X	X	X	X	X	X	SD	SD	✓	✓	X	X	X	X	X
	Pulsating Flow	?	X	✓	✓	X	X	?	X	X	X	X	X	X	X	X	✓	✓	?	?	X	X	X

* = Must be electrically conductive
✓ = Generally suitable
? = Worth consideration
X = Not suitable
SD = Some design

to the sensor. As a result, the installation is time consuming and, as a result of the many tube or pipe joints, it requires relatively high maintenance to eliminate leakage.

Reynolds Number

If the Reynolds number (Re) and flow rate are both constant, the output signal of a head-type flowmeter will also be constant. However, if the Re changes, that will also change the meter reading, even at constant flow. Therefore, it is recommended to calculate the Reynolds numbers at both maximum and minimum flows and check whether the corresponding change in flow coefficients is within the acceptable error. If it is not, a different type of sensor must be selected, such as the quadrant-edged orifice for low-Reynolds-number applications or a flowmeter type that is insensitive to Reynolds variations, such as the magnetic meter.

Figure 2.1f depicts the relationship between the pipeline Reynolds number and the discharge coefficients of various head-type flow elements. The Reynolds number can be calculated by the following equation:

$$\mathrm{Re} = \frac{3.160 G_f Q_f}{D\mu} \qquad \textbf{2.1(2)}$$

where
G_f = process fluid specific gravity (at 60°F, or 15.5°C)
Q_f = liquid flow in GPM
D = pipe inside diameter (in inches)
μ = viscosity of the process fluid (in centipoise)

As shown by Figure 2.1f, the orifice plate discharge coefficient is constant within ±0.5% over a Reynolds number range of 2×10^4 to 10^6. The discharge coefficient being constant guarantees that no measurement errors will be caused by Reynolds number variations within this range. On the other hand, if, at minimum flow, the Reynolds number would drop below 20,000, that would cause a substantial increase in the discharge coefficient of the meter and a corresponding error

TABLE 2.1d
*Flowmeter Selection Table**

	Clean Liquids	Dirty Liquids	Corrosive Liquids	Viscous Liquids	Abrasive Slurries	Fibrous Slurries	Low Velocity Flows	Vapor or Gas	Hi Temp. Service	Cryogenic Service	Semi-Filled Pipes	Non-Newtonians	Open Channel
Differential Pressure Orifice	✓	??	?	?	X	X	✓	✓	✓	✓	X	??	X
Venturi	✓	?	??	??	??	??	??	✓	??	??	X	??	X
Flow Nozzles and Tubes	✓	??	??	??	??	??	??	✓	??	??	X	??	X
Pitot Tubes	✓	??	?	??	X	X	??	✓	??	??	X	X	X
Elbow	✓	?	?	??	?	??	X	✓	??	??	X	??	X
Magnetic	✓	✓	✓	?	✓	✓	?	X	??	X	??	?	??
Mass Coriolis	✓	✓	?	✓	✓	?	?	??	??	??	X	✓	X
Thermal	??	??	??	??	??	??	?	✓	??	X	X	??	X
Oscillatory Vortex Shedding	✓	?	?	??	X	X	X	✓	??	??	X	X	X
Fluidic	✓	??	?	??	X	X	X	X	??	??	X	X	X
Vortex Precession	✓	X	??	??	X	X	X	✓	??	X	X	X	X
Positive Displacement	✓	X	??	✓	X	X	✓	✓	??	??	X	X	X
Target	✓	?	?	?	??	X	??	✓	??	??	X	??	X
Turbine	✓	??	??	?	X	X	??	✓	??	??	X	X	?
Ultrasonic Transit Time	✓	??	??	??	X	X	??	??	X	??	X	X	?
Doppler	X	✓	??	??	??	??	??	X	X	X	X	??	X
Variable Area	✓	?	?	?	X	X	??	✓	?	X	X	X	X
Weirs and Flumes	✓	?	??	X	??	??	?	X	X	X	✓	X	✓

✓Designed for this service
?? Applicable for the service under certain conditions, consult manufacturer
? Normally applicable for this service
X Not applicable for this service
*Courtesy of Fischer & Porter, which today is new ABB Process Automation.

in the measurement. Therefore, it is advisable to limit the use of orifice plates to applications where the Reynolds number stays above 20,000 throughout the flow range.

Energy Costs

In larger pipes or ducts, the yearly energy operating cost of d/p-type flowmeters can exceed the purchase price of the meter. The permanent pressure loss through a flowmeter is usually expressed in units of velocity heads. The velocity head is calculated as $v^2/2g$, where v is the flowing velocity and g is the gravitational acceleration (9.819 m/sec^2 or 32.215 ft/sec^2 at 60° latitude).

Therefore, the velocity head at, say, a flowing velocity of 10 ft/sec is calculated (in the English units) as $10^2/64.4 = 1.55$ ft of the flowing fluid. If the flowing velocity is 3 m/sec, the velocity head is calculated (in the metric units) as 32/19.64 = 0.46 m of the flowing fluid. The velocity head is converted into pressure drop by multiplying it with the specific gravity of the flowing fluid. As shown in Table 2.1g, the different flowmeter designs require different pressure drops for their operation.

One can calculate the yearly operating cost of any flow measurement installation by using the following formula:

$$\$/\text{yr} = C(\$/\text{KWH})(OT)(dP)(F)(SpG)/(\%) \qquad \textbf{2.1(3)}$$

where

C = a correction factor for the units used ($C = 1.65$ if the flow is in GPM and the pressure loss is in feet)
\$/KWH = unit cost of electricity in the area
OT = operating time of the meter (1.0 if operated continuously)
dP = pressure loss in velocity heads in the particular meter (units are feet or meters)
F = flow rate (units are in GPM or m^3/sec)
SpG = specific gravity of the flowing fluid (water = 1.0)
% = efficiency of the pump (or compressor) expressed as a fraction (70% = 0.7)

Example Let us calculate the yearly cost of operation if an orifice sized for 100-in. H_2O pressure drop ($dP = 8.333$ ft =

TABLE 2.1e
*Flowmeter Selection Table**

Flowmeter	*Pipe size, in (mm)*	*Gases (vapors)*		*Liquids*						*Temperature, °F (°C)*	*Pressure, PSIG (kPa)*	*Accuracy, uncalibrated (including transmitter)*	*Reynolds number† or Viscosity*
								Slurries					
		Clean	*Dirty*	*Clean*	*Viscous*	*Dirty*	*Corrosive*	*Fibrous*	*Abrasive*				
	SQUARE ROOT SCALE. MAXIMUM SINGLE RANGE 4:1												
Orifice										Process temperature to 1000°F (540°C); transmitter limited to −30–250°F(−30–120°C)	To 4000 PSIG (41,000 kPa)		
Square-edged	>1.5 (40)	✓	X	✓	X	?	?	X	X			±1–2% URV	R_D > 2000
Honed meter run	0.5–1.5 (12–40)	✓	X	✓	?	X	?	X	X			±1% URV	R_D > 1000
Integral	<0.5(12)	✓	X	✓	✓	X	?	X	X			±2–5% URV	R_D > 100
Quadrant/conic edge	>1.5(40)	X	X	✓	✓	?	?	X	X			±2% URV	R_D > 200
Eccentric	>2(50)	?	✓	?	X	✓	?	X	X			±2% URV	R_D > 10,000
Segmental	>4(100)	?	✓	?	X	✓	?	X	X			±2% URV	R_D > 10,000
Annular	>4(100)	?	✓	?	X	✓	?	X	X			±2% URV	R_D > 10,000
Target	0.5–4 (12–100)	✓	✓	✓	✓	✓	?	X	X			±1.5–5% URV	R_D > 100
Venturi	>2(50)	✓	?	✓	?	?	?	?	?			±1–±2% URV	R_D > 75,000
Flow nozzle	>2(50)	✓	?	✓	?	?	?	X	X			±1–±2% URV	R_D > 10,000
Low loss	>3(75)	✓	X	✓	X	X	✓	X	X			±1.25% URV	R_D > 12,800
Pitot	>3(75)	✓	X	✓	?	X	?	X	X			±5% URV	No limit
Annubar	>1(25)	✓	X	✓	X	X	?	X	X			±1.25% URV	R_D > 10,000†
Elbow	>2(50)	✓	?	✓	X	?	?	?	?			±4.25% URV	R_D > 10,000†

LINEAR SCALE TYPICAL RANGE 10:1

Magnetic	0.1–72 (2.5–1800)	X	X	✓	✓	✓	✓	✓	✓	360 (180)	≤1500 (10,800)	±0.5% of rate to ±1% URV	No limit
Positive-displacement	<12 (300)	✓	X	✓	X	X	?	X	X	Gases: 250 (120) Liquids: 600 (315)	≤1400 (10,000)	Gases: ±1% URV Liquids: ±0.5% of rate	≤8000 cS
Turbine (Dual turbine)	0.25–24 (6–600)	✓	X	✓	X	X	?	X	X	–450–500 (–268–260)	≤3000 (21,000)	Gases: ±0.5% of rate Liquids ±1% of rate (±0.1% of rate over 100:1 range)	≤2–15 cS
Ultrasonic Time-of-flight	>0.5 (12)	X	X	✓	?	X	✓	X	X	–300–500 (–180–260)	Pipe rating	±1% of rate to ±5% URV	No limit
Doppler	>0.5 (12)	X	X	X	?	✓	✓	✓	✓	–300–250 (–180–120)	Pipe rating	±5% URV	No limit
Variable-area (Dual float)	≤3 (75)	✓	X	✓	✓	X	?	X	X	Glass: ≤400 (200) Metal: ≤1000 (540)	Glass: 350 (2400) Metal: 720 (5000)	±0.5% of rate to ±1% URV (up to 20:1 range)	<100 cS
Vortex	1.5–16 (40–400)	✓	?	✓	X	?	?	X	X	≤400 (200)	≤1500 (10,500)	±0.75–1.5% of rate	R_D >10,000

cS = centiStokes
URV = Upper range value
✓ = Designed for this application
? = Normally applicable
X = Not applicable
*This material is reproduced by permission of McGraw-Hill, Inc., from R. W. Miller's *Flow Measurement Handbook*, 2nd edition, 1989.
†According to other sources, the minimum Reynolds number should be much higher.

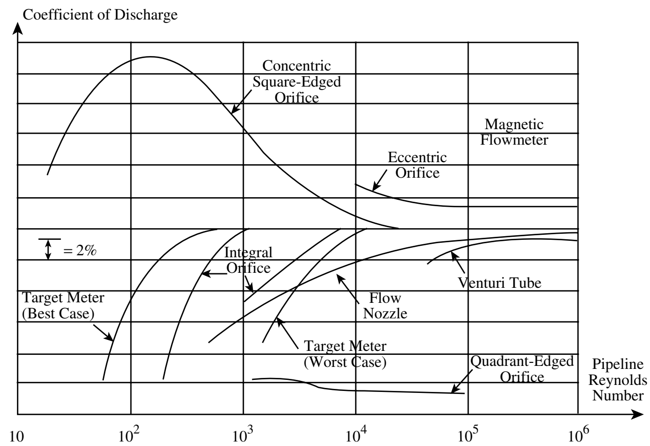


FIG. 2.1f
Discharge coefficients as a function of sensor type and Reynolds number. (Courtesy of The Foxboro Co.)

TABLE 2.1g
Velocity Head Requirements of the Different Flowmeter Designs

Flowmeter Type	*Permanent Pressure Loss (in Velocity Heads)*
Orifice plates	Over 4
Vortex shedding	Approximately 2
Positive displacement	1 to 1.5
Turbine flowmeter	0.5 to 1.5
Flow tubes	Under 0.5

3.6 PSID) in a 16-in. schedule 40 steel pipe is measuring the flow of 5000 GPM of water flow. The meter is operating continuously ($OT = 1.0$), the cost of electricity is \$0.1/kWh, and the pump efficiency is 60% (% = 0.6).

$$\$/yr = 1.65(0.1)\,(1.0)\,(8.333)\,(5000)\,(1.0)/0.6 = \$11{,}457 \text{ per year} \qquad \textbf{2.1(4)}$$

If the cost of electricity is \$0.1/kWh and the pumping efficiency is 60%, the operating cost of any continuous pressure drop in any water pumping system can be calculated as

$$\$/yr = 0.635\ (GPM)\ (PSID) \qquad \textbf{2.1(5)}$$

Therefore, when selecting a flowmeter, we should consider not only the purchase and installation costs but also the operating cost during the life of the flowmeter. As was shown above, a major component of the operating cost of flowmeters is their pumping (or compressor operating) energy costs.

In the following paragraphs, the main advantages and disadvantages of the large family of d/p measurement-based flow sensors (Figure 2.1h), this most widely used flowmeter category will be discussed. The discussion here will be limited to the highlights of sensor features. For an in-depth discussion of their features and characteristics, the reader should turn to the appropriate section in this chapter that is devoted to the particular design.

Orifice Plates

Orifice plates are the simplest and least expensive flow element within the d/p-type sensors. The total installed cost is relatively independent of pipe diameter, because the cost of the piping manifold and the differential-pressure readout or transmitter are unaffected by pipe size and are relatively constant. Consequently, the orifice-type installations are relatively expensive in smaller pipe sizes and rather economical in pipe sizes over 6 in. (150 mm).

Orifices can be used in a wide range of applications, because these plates are available in a variety of materials and in many designs, such as concentric, segmental, or eccentric. Another advantage is that the orifice plate can be badly worn or damaged, yet it will still provide a reasonably repeatable output, albeit significantly inaccurate. Another very convenient feature of the orifice-type installation is the ability to service or replace the readout or transmitter without the need to remove the orifice or to interrupt the process flow.

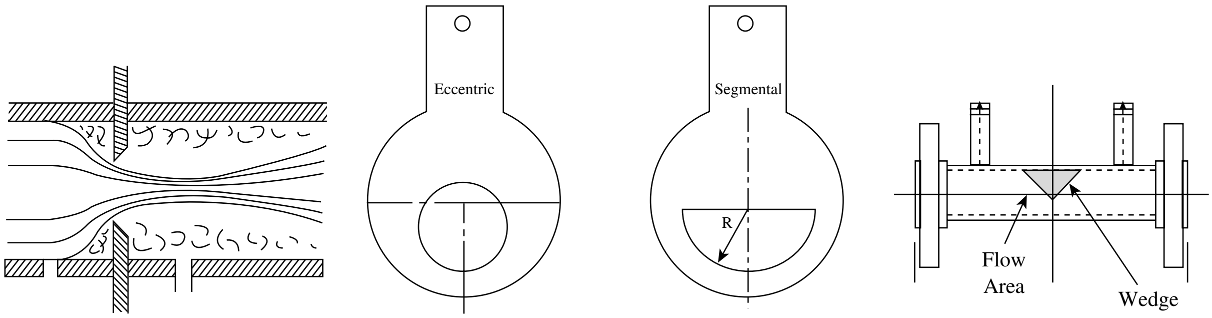
The main disadvantages are the low accuracy[5] (Figure 2.1i) and low rangeability of standard orifices, although substantial improvements been reported (error under 1% of actual flow over a 10:1 range) when intelligent and multirange d/p cells are used. Other disadvantages of orifice-type installations include the high irrecoverable pressure loss (40 to 80% of the generated head) and the deterioration in both measurement accuracy and in long-term repeatability as the edge wears or as deposits build up. High maintenance is another disadvantage in installations where manifold leakage or pressure tap plugging are likely.

Orifice-type flow measurement has been modified, and new, special-purpose devices have been introduced to meet particular process requirements. One such unique design is the annular orifice used to measure the hot and dirty gases in the steel industry. Here, the process flow passes through an annular opening between the pipe and a disk-shaped, concentrically located plate, and the pressure difference is detected between the upstream and downstream faces of that disk. This design is shown in the section on target meters.

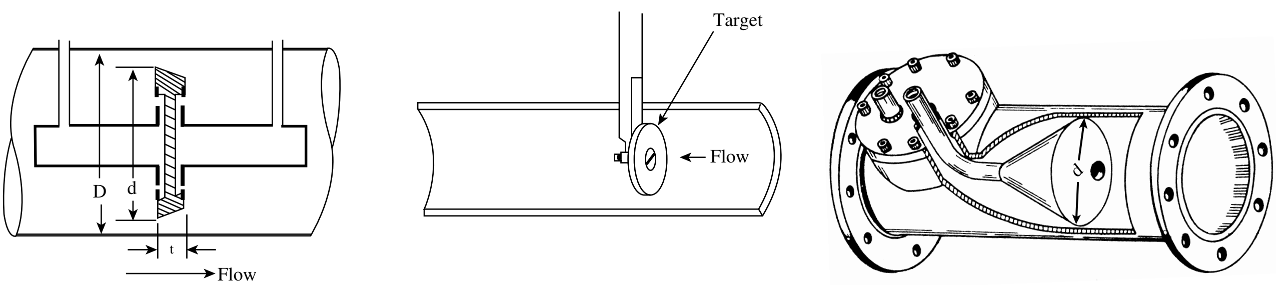
For paper pulp or slurry flow detection, the segmental and eccentric orifices (Section 2.15), venturi cones (Section 2.28) and the segmental wedge elements (Section 2.21) have been developed. The venturi cone is shaped as a restriction in the center of the flow path, forcing the flowing stream into an annular space between the cone and the pipe. The segmental wedge element restricts the flow passage, because the top of the pipe is indented. These sensors are all used on dirty fluids or fluids at higher temperatures.

Venturi Tubes and Nozzles

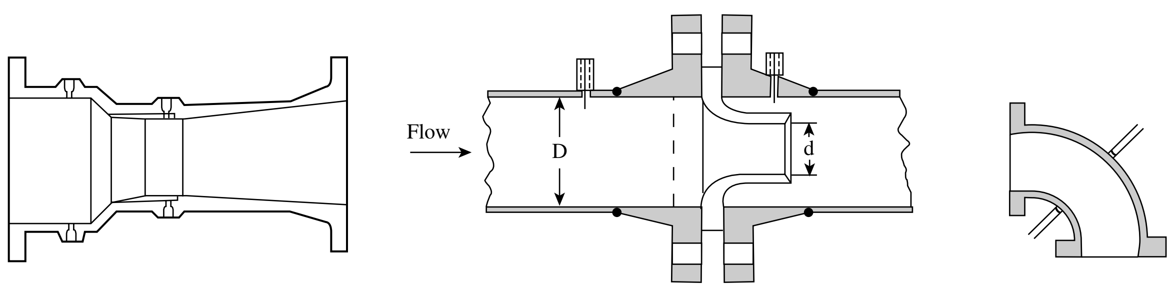
The shapes of these tubes and nozzles have been obtained with the goal of minimizing the pressure drop across them. These tubes are often installed to reduce the size of (and therefore capital expenditures on) pumping equipment and to save on pumping energy costs. In contrast with the sharp-edged



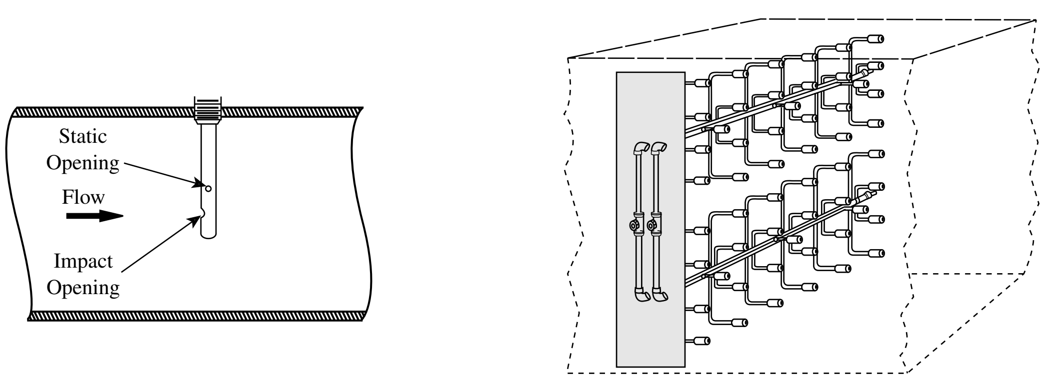
a) Sharp-edged, eccentric, segmental orifice and wedge designs



b) Annular, target and V-cone designs



c) Venturi tube, flow nozzle and elbow tap designs



d) Conventional and area-averaging pitot tube designs

FIG. 2.1h
Pressure difference producing flowmeter designs.

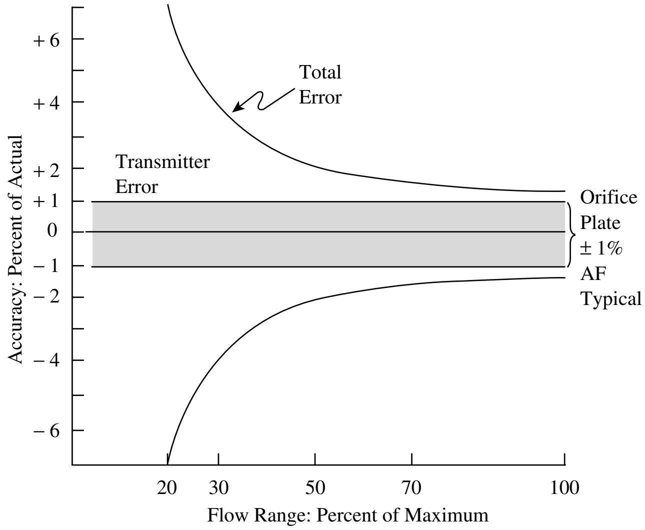


FIG. 2.1i
Total error of an orifice type flow measurement, using a ±1/2% full-scale d/p cell, is shown as a function of actual flow.

orifice, these tubes and nozzles are resistant to abrasion and can also be used to measure the flow of dirty fluids and slurries. They are, however, considerably larger, heavier, and more expensive than the orifice plate. Their installation is also more difficult.

Flow nozzles represent a transition between orifices and flow tubes. They are less expensive, but they produce more head loss than do the flow tubes.

Sonic Venturi Meters

A flowmeter with very high rangeability can be obtained when the venturi tubes are inserted into a multiport digital control valve (illustrated in Figure 2.1j) in which the area of each port is twice the size of the next smaller one. The on/off ports are opened through binary manipulation and, therefore, the meter rangeability is a function of the number of ports used. With 8 ports, the rangeability is 255:1; with 10, it is 1023:1; with 12 it is 4095:1; and so on. The digital control valve is converted into a flowmeter by inserting a sonic velocity venturi into each of the ports. A sonic velocity venturi element passes a known and constant flow rate when the flow velocity at its throat reaches sonic velocity. Therefore, this flowmeter requires that the meter pressure drop continuously exceed 40% of the absolute upstream pressure to guarantee the continuous presence of sonic velocity of the throat of the venturi tubes. Because of the inherent requirement for this high pressure drop, this meter is ideal for applications in which it is desirable to lower pressure as well as to measure the flow.

The accuracy of the sonic venturi is 1/2 to 1% of actual flow throughout the meter range. With the addition of inlet gas pressure, temperature, and/or density sensors, it can be converted for mass flow measurement. The sonic venturi can also meter the flow of liquids. This flowmeter is available in sizes from 1 to 8 in. (25 to 200 mm). Units have been built

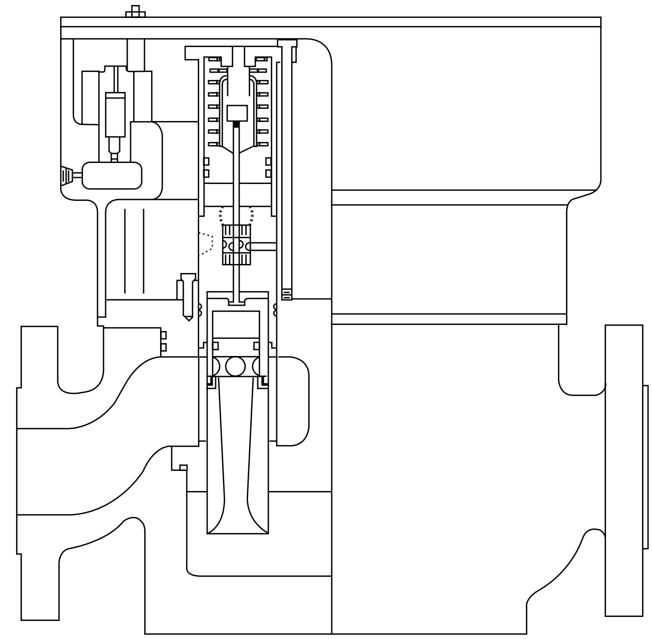


FIG. 2.1j
Sonic venturi digital flowmeter featuring extremely wide rangeability.

for up to 10,000 PSIG (69 MPa) pressure services and for temperatures from cryogenic to 1200°F (650°C).

Pitot Tubes

A pitot tube is a small, open-ended tube, that is inserted into the process pipe with its open end facing into the flow. The differential between the total pressure on this open impact port and the static pipeline pressure is measured as an indication of flow. For the measurement of large flows, the pitot-tube-type sensors provide a very low-cost measuring system with negligible pressure loss. They are also convenient for temporary measurements and for traversing pipes and ducts to obtain their velocity profiles. Their principal limitation is that they measure the flowing velocity at only one point and therefore, even after calibration, they will be in error every time the velocity profile changes. Therefore, they are used only when low-accuracy volumetric readings are acceptable, such as in HVAC applications. They are also subject to plugging and therefore require substantial maintenance.

To reduce the effect of velocity profile changes and thereby improve the measurement accuracy, multiple-opening pitot tubes and area-averaging pitot traverse stations have also been developed.

Elbow Taps

Elbow taps measure the flow rate by detecting the differential pressure between taps located on the inner and outer radii of an elbow. In larger pipes, this results in a very low-cost installation, because pipe size does not affect cost. This is a crude, inaccurate measurement, requiring high flow velocities and long upstream, straight pipe lengths.

Target (or Impact) Meters

In a target flowmeter, a target or impact plate is inserted into the flowing stream, and the resulting impact force is detected electronically or pneumatically as an indication of flow. The target meter installations are more expensive than orifices but because (in case of the target design) there are no pressure taps to plug, they are better suited for applications in which the process fluid is "sticky" or contains suspended solids. The other advantage is that they have no moving parts. Their accuracy and rangeability (3:1) are low, but they can be reranged.

ELECTROMAGNETIC METERS

Magnetic flowmeters operate in accordance with Faraday's law, because these meters measure the velocity of electrically conductive liquids as they cut the magnetic fields that are maintained across these metering tubes. The main advantages of magnetic flowmeters include their completely unobstructed bore and their lack of moving parts. Because of these features, they introduce no pressure loss and experience no wear and tear on their components. Other advantages include their chemical compatibility with virtually all liquids; indifference to viscosity, pressure, temperature, and density variations; ability to provide linear analog outputs and to measure bidirectional flows; availability in a wide range of sizes; and ease and speed of reranging on site.

Their major limitation is that they can be used only on electrically conducive fluids. (This requirement eliminates their use on all gases and on most hydrocarbon fluids.) Another disadvantage is their high purchase price and the cost of maintaining the magnetic field. To locate the flow tube in an explosion-proof area, the converter and power supply must be remotely located, and intrinsic safety barriers must be installed between them and the tube.

Electromagnetic flowmeters are often recommended for applications involving corrosive aqueous liquids and slurries. In their more recent designs, the magnetic flowmeter probes are provided with electrode cleaners, and the magnetic field is cycled so as to conserve electric energy and to allow automatic rezeroing, which guarantees better accuracy. The use of ceramic flowtubes has reduced their costs while eliminating electrode leakage, because the sintered electrodes cannot leak. The addition of intelligence through digital chips has allowed double-range operation, increased turndown, guaranteed the detection of empty pipes, and reduced the measurement error to within 0.5% of actual flow over a 10:1 range.

TURBINE METERS

In turbine meters, a digital output is generated, which is linear with the process flow, as the speed of rotation of the turbine is measured. Turbine meters can be used in both liquids and gases, and they are suitable for the measurement of both very low and very high flow rates, as insertion designs. The liquid turbine meter is one of the most accurate meters available for low- to medium-viscosity products. Rangeability of single turbine meters is around 10:1, for dual-turbine meters, it exceeds 100:1. Turbine meters can be used under practically any pressure and for applications involving extremely high and low temperatures. They are easy to install and, relative to the pipe diameter, are also small in size and weight. The meter provides a very fast response speed and is suitable for hygienic applications.

Their principal limitations include high cost, incompatibility with viscous or dirty liquids, and the potential for being damaged by over-speeding if slugs of gas or vapor are sent through the liquid meter. The installation of upstream filters is often recommended, in spite of the fact that it increases both the pressure drop and the maintenance requirement of the installation.

Turbine meters are widely used when high-accuracy measurements are required in applications involving product sales. They are also used when high accuracy is required in blending, on test rig duty, and in general measurement. Variations on the basic turbine flowmeter design include nonelectric (fiber optic) detectors; turbine probes; bearingless "hover-flow" designs; and various paddlewheel, impeller, and shunt-flow designs. The impeller and paddle-flow designs cost less but also provide less accuracy than traditional turbine flowmeters.

VORTEX METERS

While fishing in Transylvania, Theodore von Kármán noticed that, downstream of the rocks, the distance between the shed vortices was constant, regardless of flow velocity. From that observation evolved the three types of vortex meters: the vortex shedding, the vortex precession, and the fluidic oscillation versions. All three types detect fluid oscillation. They have no moving components and can measure the flow of gas, steam, or liquid. Their advantages include good accuracy and repeatability, high rangeability, low maintenance, and the ability to provide either frequency or linear analog outputs.

Vortex flowmeters cannot be used to measure the flow of viscous or dirty process fluids. These flowmeters are also limited to sizes under 12 in. (300 mm), because the frequency of fluid oscillation drops off as the line size increases. The other limitation is that vortices do not form at Reynolds numbers below 10,000; therefore, this meter cannot be used in low-Reynolds-number applications.

Vortex shedding meters can be general-purpose, economically competitive alternatives to the orifice plate, and they are also used in many more demanding applications because of their superior accuracy and rangeability.

VARIABLE-AREA METERS

Variable-area meters are widely used for applications in which small flow rates are to be measured or where local indication is required. They are also common in purge meter installations, test rigs, and general industry. Variable-area meters are available in both glass and metal tube construction.

In the glass tube design, the position of the float can be visually observed as an indication of flow rate.

The main advantage of the glass tube design is its self-contained nature, which eliminates the need for power supplies. Other advantages include their low cost, low pressure loss, direct flow indication, and the ability to detect very low flow rates of both gases or liquids, including viscous fluids.

The limitations of all variable-area meters include the need for vertical mounting and that they are available only in smaller sizes. The disadvantages of the glass tube design also include its low accuracy, the limited availability of transmitters, and the design's relatively low pressure ratings.

The metallic tube units are readily available as transmitters and can be obtained in larger sizes, with higher pressure ratings. They provide good rangeability (5:1) and a linear output, but they, too, are limited to use with clean fluids and must be mounted vertically.

A wide variety of the types of designs exist in which gravity has been replaced by spring loading. In these units, an increase in flow results in a compression or deflection of a spring, and this motion is used to operate the display. These units can be mounted in any position, including horizontally, as flow-through pipeline devices.

POSITIVE-DISPLACEMENT METERS

Positive-displacement (PD) meters are often used when accurate quantities need to be delivered, either for reasons of recipe formulation in batch processes or for accounting purposes during sales. The PD meters trap a fixed volume of fluid and transfer it from the inlet to the outlet side of the meter. The number of such calibrated "packages" of fluid is counted as a measure of volumetric flow. Design variations include the rotary piston, oval gear, sliding vane, and reciprocating piston types.

Liquid PD meters offer good accuracy and rangeability (>10:1) and are particularly suited to measure the flow of high-viscosity fluids. These meters provide local readouts and do not require a power supply. When operated as a transmitter, the PD meter's output signal is linear with flow.

The PD meter applications are limited to clean fluids, because their operation depends on close meshing surfaces. Another disadvantage of PD meters is that they require regular recalibration and maintenance, particularly when used to measure the flow of nonlubricating liquids. Another disadvantage is that they are bulky and heavy. Their installed cost is high because, in addition to block and bypass valves, they also require filters and air releases for proper operation.

ULTRASONIC METERS

Ultrasonic meters are ideally suited to measure the flow of very corrosive liquids. They are available in two forms: Doppler and transit-time version.

In case of the Doppler meters, an ultrasonic pulse is beamed into the pipe and is reflected by inclusions such as air or dirt. The Doppler meter is frequently used in a "clamp-on" design, which can be attached to the outside of existing pipelines. It detects the flowing velocity only in a small area where the sonic beam enters the flowing stream. Therefore, if that velocity is not representative of the full cross section of the pipe, the measurement accuracy will be poor. Its main advantage is its low cost, which does not increase with pipe size. Its main limitation is that it is not suitable for the measurement of clean fluids or clean gases.

The transit-time type ultrasonic flowmeters are often found in water treatment and chemical plant applications. Here, single or multiple ultrasonic beams are sent at an acute angle across the flowing stream, first in the same direction as the flow and then in the opposite direction. Flow rate is detected as the difference in transit times. This type of ultrasonic meter is considerably more expensive than the Doppler version, but it offers better accuracy. Unlike the Doppler meter, it is usable only on relatively clean fluid applications. Its advantages include that it introduces no restriction or obstruction to flow, so its pressure drop is low. One limitation is that its performance is a function of the piping configuration, and it requires fairly substantial upstream, straight runs (about 15 pipe diameters).

METERING PUMPS

Metering pumps serve the purposes of both pumping and metering. They usually are used to accurately charge relatively small quantities of clean fluids. Their two basic design variations are the plunger and diaphragm versions. The plunger pump provides better accuracy, whereas the diaphragm type is preferred for dangerous or contaminated fluid services. Their advantages include that they are self-contained, easy to install, and generally provide good accuracy. Metering pump performance is a function of both the process fluid (which must be clean and contain no bubbles) and the process conditions (which must be constant in pressure and viscosity to keep the leakage flow constant). Other disadvantages include their high cost, the need for periodic recalibration, and the requirement for such accessory equipment as filters and air-releases.

MASS FLOWMETERS

The measurement of mass flow can be obtained as the product of volumetric flow and density or as a direct measurement of the mass flow of the flowing process gas, liquid, or solids.

The mass flow of homogeneous gases is most frequently measured by thermal flowmeters. The main advantage of these detectors is their good accuracy and very high rangeability. The main disadvantage is their sensitivity to specific heat variations in the process fluid due to composition or temperature changes. If not compensated for, these changes will register as changes in mass flow. Thermal devices, such as the hot wire anemometers and thermal flow switches, can also detect volumetric flow rates and the flow velocities of process streams.

The mass flow of liquids and gases can be directly detected by angular-momentum devices or indirectly through the measurement of volumetric flow and density. These traditional methods have, in recent years, been overshadowed by the Coriolis mass flowmeter. These units detect the twisting of an oscillating, usually stainless steel, flow tube. This twist is a function of the mass flow through the tube. Coriolis meters can operate at process flow velocities from 0.2 to 20 ft/sec (0.061 to 6.1 m/sec) and therefore can provide a rangeability of 100:1. Their accuracy is also high (0.2% of actual flow), their pressure and temperature ratings are acceptable, and, in addition to the mass flow output signal, they can be provided with additional outputs for signaling alarm conditions or detecting the process fluid's density.

Some limitations include their relatively small sizes (up to 6 in. [150 mm]), their vibration sensitivity, and the inability to handle high-temperature process fluids (over 400°F [205°C]). The Coriolis-based mass flowmeters are very popular in the measurement of fuel flows and reactor feed flows, and in other measurements where the mass rather than the volume of the process flow is of interest.

At low flow rates, the Wheatstone-type mass flowmeter can measure flow within an error of ±0.5% of actual flow over a 100:1 range.

The mass flow of solids in gravity flow installations can be detected by impact flowmeters, which are relatively low-accuracy devices. Better accuracy and rangeability are provided by belt-type gravimetric feeders, which measure both the speed and loading of the moving belt. In addition, the loss in weight-type systems can also measure the mass flow of liquids or solids by differentiating the load cell signal from tank weighing systems. The rate at which the total weight is dropping is the mass flow out of the tank. These systems do not provide high precision and are recommended for the measurement of hard-to-handle process flows, because they do not make physical contact with the process stream.

Cross-correlation flowmeters are available for the measurement of mass flow of solids in pneumatic conveying systems or for volumetric flow measurements. The cross-correlation flowmeter uses statistical means to average the time it takes for particles in a fluid to travel a known distance. The meter can be noninvasive and is suitable for the measurement of the flow of solids and two-phase flows, including heavy slurries and very corrosive and difficult liquid-flow measurement applications. Their disadvantages include high cost, a fairly high minimum requirement on the operating Reynolds number, and poor accuracy.

LOW-FLOW APPLICATIONS

The measurement and control of low flow rates is a requirement in such applications as purging, in bioreactors, in leak testing, and in controlling the reference gas flow in chromatographs or in plasma emission spectrometers.

The most traditional and least expensive low-flow sensor is the variable area flowmeter, which is frequently made out of a transparent acrylic material. It has a high rangeability (10:1) and requires little pressure drop. Due to its relatively low accuracy, it is most often used in purge and leak-detection applications.

A much more accurate low flow detector and controller in gas metering applications is the sonic flow nozzle. This nozzle accurately maintains constant flow as long as sonic velocity is maintained, which is guaranteed by keeping the inlet pressure at about 50% over the outlet pressure. The disadvantages of the sonic nozzle include its high cost and high pressure drop. Another disadvantage is the difficulty in modulating the flow rate.

In laminar flow elements, the pressure drop and flow are in a linear relationship. The laminar flow element can be used in combination with either a differential-pressure or a thermal type of flow detector. These flowmeters provide better rangeability at about the same cost as sonic nozzles. They have a 100:1 rangeability, and control capability is readily available. Another advantage of thermal flowmeters over sonic nozzles is their inherent capability to detect mass flow. Thermal flowmeters also can directly detect low-mass flows without any laminar elements. In that case, they are installed directly into the pipeline as either thermal flowmeters or anemometers.

SPECIFYING THE KEY REQUIREMENTS

Inaccuracy

The accuracy of a flow detector is one of its most important features. One should not specify accuracy in such vague terms as "best possible" or "better than one-quarter percent" because (1) these statements are not explicit and (2) if taken at face value, they could severely limit the meter choice and result in unnecessarily high costs. Therefore, the metering accuracy should be specified precisely and at a realistic value.

In some instances—for example, in case of repetitive batch dispensing—absolute accuracy is of no critical consequence, provided that the long-term reading of the meter is stable and repeatable. In such applications, absolute accuracy is less important than long-term repeatability. In other applications, where absolute accuracy is important, one should clearly specify the flow range over which the specified error limit applies. If the error limit is given as a percentage, it should be clearly stated whether it is based on full scale (%FS) or on actual reading (%AR). It is also important to distinguish the accuracy requirements for the meter from the expected installed performance, which can be affected by variations in the properties of the flowing stream, piping configurations, and other factors.

The comments made about accuracy in Section 1.5 (Chapter 1) are also applicable to flow sensors. As stated there, one should always define the flow range over which the accuracy statement applies. As illustrated in Figure 2.1k, in case of %FS sensors, the absolute error increases as the flow rate drops.

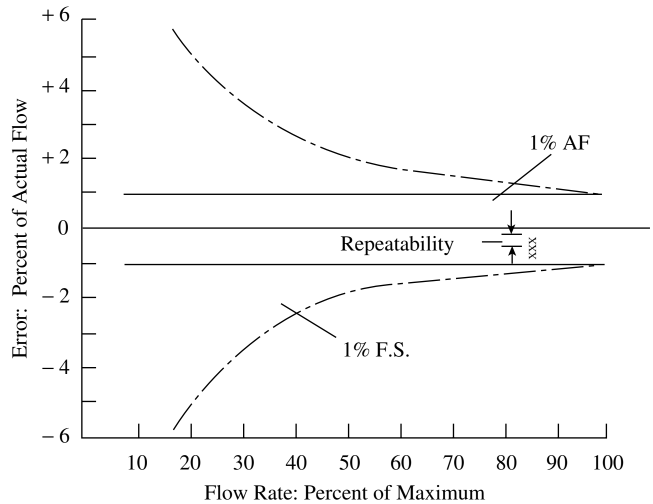


FIG. 2.1k
Comparison of 1% F.S. inaccuracy with 1% of flow inaccuracy.

Therefore, in a properly prepared specification, the accuracy requirement should state both the required flow range and the allowable error. Such a specification might read "1% AF from 10 to 100% flow" or "0.5% FS from 5% to 100% flow."

If a flow detector is nonlinear, that nonlinearity must be corrected for; otherwise, it will degrade the measurement accuracy. Linearity is the extent to which the relationship between the flow and the meter output approaches a straight-line relationship. The linearity of a flow sensor is often different during factory calibration as compared with under the installed conditions in the field.

The vendor's published data on meter performance is generally based on ideal installation and operating conditions. Therefore, although the meter is capable of achieving that performance level, there is no guarantee that it will realize it under actual operating conditions. For example, insufficient upstream straight piping can result in substantial swirling, which will cause a deterioration in the linearity of the meter and will therefore shift the calibration constant of the meter. Consequently, the manufacturer's installation recommendations should be followed carefully, or, if this is not possible, the likely deterioration in performance should be evaluated and determined to be acceptable before making the installation.

Changes in fluid characteristics can also alter the meter's performance. Figure 2.1l for example, illustrates the effects of viscosity variations between 0.3 and 25 CTP on the performance of two of the most accurate flow detector types, the turbine meter and the positive-displacement meter. In case of the turbine meter, an increase in viscosity lowers the measurement accuracy; in case of the PD meter, it improves the performance, and it is the reduction in viscosity that causes a deterioration in the performance. For any application, the acceptability of the consequences of the expected operating conditions should be verified in advance.

Wear, drift, and expected shifts in calibration should also be investigated, and the corresponding maintenance costs

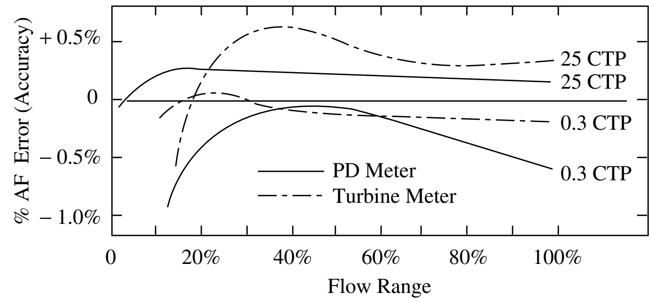


FIG. 2.1l
Differing effects of viscosity variation on a turbine meter and a positive displacement meter (CTP = centiPoises).

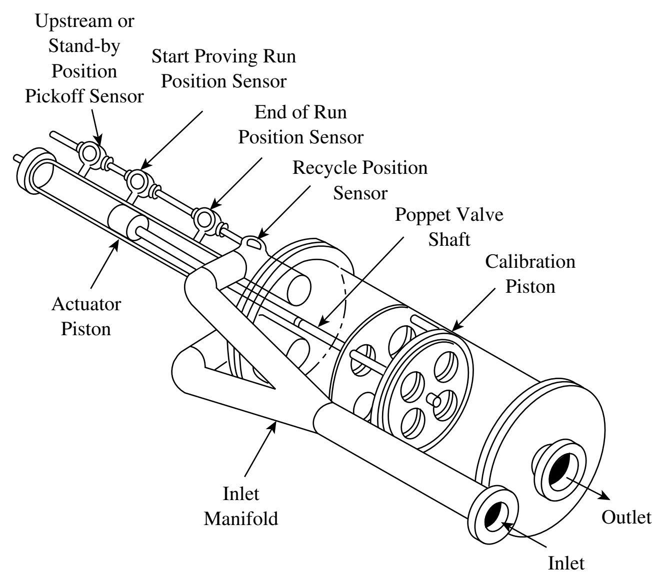


FIG. 2.1m
Inline ballistic flow prover. (Courtesy of Brooks Instrument Div. of Emerson Electric.)

evaluated, when considering alternative meter options. In critical applications, one might consider the installation of automatic on-stream recalibration equipment. Figure 2.1m illustrates an in-line ballistic prover that can recalibrate a flow detector without requiring an interruption of the process flow.

Safety

Safely is one of the most important considerations in the selection of any industrial equipment. In case of flow detection, all meter components must be certified as suitable for the applicable electrical area classification for the location at which they will operate. Meeting such requirements may be achieved by installing purely mechanical or pneumatic devices or, more commonly, by selecting intrinsically safe, flameproof, or explosion-proof devices.

Other safety aspects (often overlooked) are the safety of the selected materials of construction and the possible safety consequences of leakage. Fluids such as oxygen or liquid chlorine can cause explosions, because they react with certain materials. If the heat of such reactions cannot be removed, and especially if the resulting pressure is confined, violent explosions can result. Therefore, various organic and inorganic substances, including ordinary lubricants such as oil, grease, and wax, can cause explosions in the presence of oxygen or chlorine. It is therefore essential that any flowmeter operating in such services be thoroughly cleaned and degreased.

The choice of the materials of construction is also critical for applications involving high concentrations of oxygen. The use of steels, for example, presents an explosion hazard, which increases with a rise in the velocity and pressure of the flowing oxygen. The maximum allowable velocity and pressure in such applications depends on the cleanliness and surface finish of the working components. Therefore, clean steel with high surface finish can be used at higher pressures and flow rates than can regular steel. Yet, the best protection is to select such alternative materials as phosphor bronze, gun metal, brass, beryllium, copper, and so forth.

To protect the operators, it is essential that leakage of noxious or dangerous fluids be eliminated or kept to an absolute minimum. The addition of every joint increases the probability of leakage. Therefore, the presence of manifolds, pressure taps, and fragile components all add to the probability of leakage. Therefore, when metering dangerous or noxious materials, nonpenetrating flowmeter designs are preferred.

Installation

Installation requirements vary dramatically among the various meter types and can be the deciding factors in meter selection. The most demanding applications are ones in which the process flow cannot be stopped and the measurement point cannot be bypassed. In such applications, the selection choice is limited to clamp-on meters, such as the ultrasonic Doppler or the cross-correlation design, and to the hot-tap insertion meters, such as the various probe designs.

Even if block and bypass valves can be installed around the meter, the installation requirements still affect both cost and plant acceptability. One critical consideration is the availability of the requisite straight upstream and downstream pipe lengths. If they are not available, it is necessary to derate the performance of the meter or to consider an alternative design such as an electromagnetic sensor, which requires only the equivalent of 5 pipe diameters in straight upstream piping.

Specific application requirements affect different meters in different ways. For example, if an electric power supply is not available at the measurement point, this eliminates the electromagnetic flowmeter from consideration. If a vertical pipe section cannot be provided, one cannot consider the variable area meter. A positive-displacement meter requires a strainer, often an air release, and so on. Even if the meter installation requirements can be met, their effect on the overall system cost must still be considered and quantified, because the selection should consider the total cost, which should include installation, operation, and maintenance expenses.

Cost

Cost is a critical factor in the selection of any equipment. To arrive at a “reasoned” decision, one should not evaluate the purchase price only. Other factors, such as operating costs, maintenance, spare parts inventory, the effect of downtime, and many others, should all be considered if a reasoned decision is to be reached. Hardware costs, in general, should always be balanced against the potential benefits of increased plant efficiency or product quality. These benefits are usually by-products of increased sensor accuracy, repeatability, and rangeability, which all tend to increase metering costs.

When evaluating the various flowmeter choices, the cost comparison should be based on the total system cost and not merely the flowmeter price. Not only should such costs as the expenses for providing separate converters or transmitters be included, we should also consider the cost of ancillary items such as straight upstream and downstream piping, flow conditioning and filtering equipment, electric power supplies, and so on. The cost of installation also varies with local labor rates and can be a significant factor in the meter selection process.

Operating costs are also an important consideration. Operating costs are affected by the amount of routine service required and by the level of maintenance personnel needed. These costs also increase if special tools such as flow simulator equipment are required and are not already available.

In addition to the preceding, we should consider the versatility of the selected meter. We should determine whether the secondary units required for the particular device can also be used on other meters. We should check whether the meter can be used in other applications and determine the ease with which it can be reranged. Spare parts requirements should also be reviewed to establish both the value of the required inventory and whether the spares will be interchangeable with other meter sizes and models. And we should also consider the estimated total life of the meter (which tends to be shorter if there are moving components) and review the coverage of the guarantee provided for the meter.

The pressure loss through the meter is also part of its total operating cost. If we are comparing an orifice plate and a low-loss flow tube, the initial cost of the orifice plate is much lower; however, because of the head loss, its total cost can be higher. As was discussed earlier, pumping cost is a function of flow rate, electricity costs, pumping efficiency, and pressure loss. Consequently, the higher the pressure drop across the flow sensor, the higher will be the pumping costs throughout the life of the installation.

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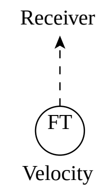
2.2 Anemometers

D. S. KAYSER (1982) **J. KOZÁK** (1995) **B. G. LIPTÁK** (2003)



Flow Sheet Symbol

Types	A. Pitot B. Mechanical B1. Vane B2. Cup B3. Propeller or turbine C. Thermal D. Doppler D1. Acoustic or ultrasonic D2. Laser
Applications and Designs	Hand-held air velocity sensors are used in HVAC applications; transmitting anemometers are utilized in industry and as wind speed monitors
Airflow Velocity Ranges, Given in Feet per Minute (ft/min)	(1 ft/min = 0.3048 mpm = 0.0183 km/h = 0.0114 mph = 0.0167 ft/sec = 0.005 m/sec = 101.2 knots) A. 0 to 300, 0 to 1250, 0 to 2500, 0 to 5000, and 0 to 10,000 are standard ranges; total capability is 25 to 30,000 B1. 300 to 3000 is standard; can cover 30 to 12,000 B2. 0 to 15,000 B3. 0 to 13,000 C. 20 to 500, 50 to 1000, 100 to 2000, and 0 to 6000 are standard ranges; stack flow probes can go up to 18,000 D1. 0 to 7000 D2. 0 to 60,000 or up to supersonic
Wind Measurement Heights	A, B, and C. Detect wind velocities at the elevation of the tower height D1. Measures wind velocity in strata of 150 ft (50 m) thickness from 200 to 2000 ft (60 to 600 m) and sometimes up to 5000 ft (1500 m)
Inaccuracy	A. 2 to 3% of full scale B1. From 1% of reading to 2% of full scale C. 2% of full scale D1. 1% of full scale
Costs	Hand-held pitot, thermal, and mechanical anemometers range from \$500 to \$2500. Sensor probes alone cost about \$300 to \$500; combined units reading air velocity, humidity, and temperature are available from \$800 to \$3000. A vane-type probe with a 4- to 20-mA DC transmitter with a 1.5% full-scale error is about \$2500. Thermal stack flow probes for wet and dirty gas applications cost about \$5000. Doppler acoustic sounders for remote sounding of wind profiles range in cost from \$15,000 to \$90,000; average cost is about \$50,000. Laser Doppler units range from \$25,000 to \$45,000.
Partial List of Suppliers	ABB Instruments Inc. (www.abb.com/us/instrumentation) (A) Air Instruments & Measurements Inc. (www.aimanalysis.com) (B, D) Air Monitor Corp. (www.airmonitor.com) (A) Alnor Instrument Co. (www.alnor.com) (B1, C) Anderson Instrument Co. (www.andinst.com) Cole-Parmer Instrument Co. (www.coleparmer.com) (A, B, C)

Dwyer Instruments Inc. (www.dwyer-inst.com) (A, C)
Eldridge Products Inc. (www.epiflow.com) (C)
The Foxboro Co. (www.foxboro.com) (A)
Intek Inc. (www.intekflow.com) (C)
Kobold Instruments Inc. (www.koboldusa.com) (A)
Kurz Instruments Inc. (www.kurzinstruments.com) (C)
Meriam Instrument (www.meriam.com) (A)
Mid-West Instrument (www.midwestinstrument.com) (A)
Sierra Instruments Inc. (www.sierrainstruments.com) (C)
TSI Inc. (www.tsi.com) (B, C, D2)
United Electric Controls Co. (www.ueonline.com) (A)
Vaisala Inc. (www.vaisala-usa.com) (B1, 2)

Anemometers are used to measure air and gas flows in a variety of applications, including such tasks as the balancing of HVAC systems using hand-held air velocity meters. They are also used in stacks to measure the velocity of wet and dirty gases and in wind detection applications to obtain three-dimensional wind velocity profiles using Doppler-type sensors. Anemometer designs include pitot, mechanical (vane, cup, propeller, turbine), thermal, and Doppler types. Pitot tubes and thermal flowmeters are discussed later in this chapter. This section concentrates on the mechanical and Doppler-type anemometers.

MECHANICAL ANEMOMETERS

Figure 2.2a illustrates the vane design. Airflow causes the vanes to rotate with an angular velocity that is proportional to the wind speed. When a portable unit is required, or when the local readout is satisfactory, vane velocity is sent to a local indicator through a gear-and-spring assembly. When remote readouts are required, a magnetic or capacitive coupling is used to generate a transmission signal.

Figure 2.2b shows a three-cup anemometer, which is insensitive to wind direction. In one design, the shaft drives a direct current (DC) tachometer, which generates an output voltage that is proportional to the wind speed. This signal can be used as the input to a remote mounted indicator or recorder. The impeller design shown in Figure 2.2c is also provided with a shaft-driven tachometer. Because the tail of this impeller design always points the impellers into the wind, this instrument can detect both wind speed and wind direction.

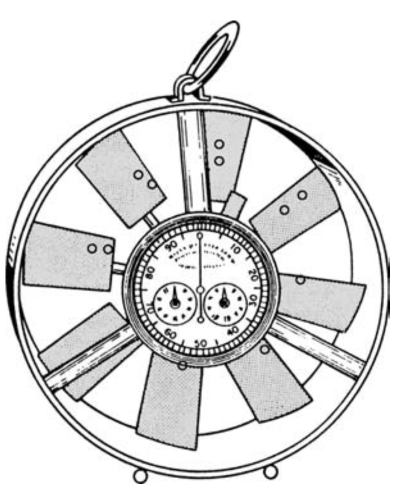


FIG. 2.2a
Vane anemometer with local readout.

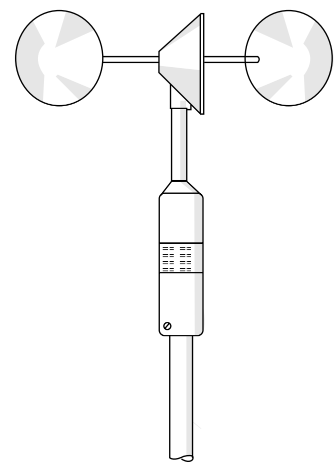


FIG. 2.2b
Three-cup anemometer.

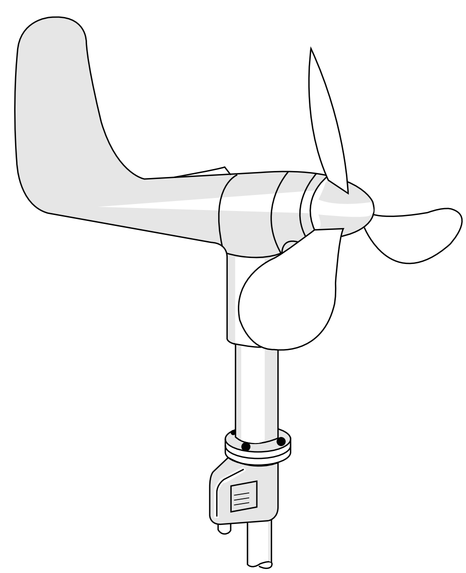


FIG. 2.2c
Impeller anemometer.

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 feet. A typical distance constant for commercially available units is 6 ft (1.8 m).

THERMAL ANEMOMETERS

The thermal flowmeters are discussed in some detail later in this chapter and therefore are only briefly mentioned here. The hot-wire anemometer (Figure 2.2d) operates as a heated thermopile that is cooled at a rate that is proportional to the air (or gas) velocity at the probe tip. It is available in ranges of 100 to 2000, 50 to 1000, and 20 to 500 ft/min (0.5 to 10.0, 0.25 to 5.0, and 0.1 to 2.5 m/sec, respectively).

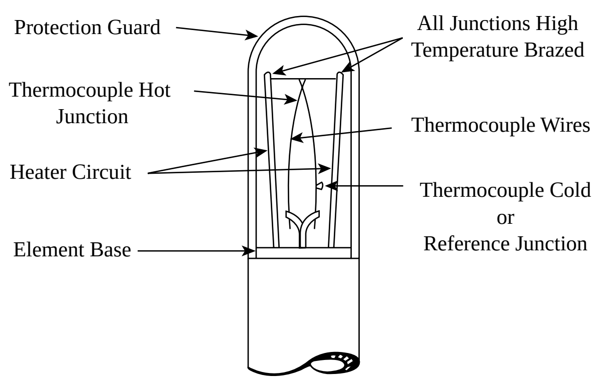


FIG. 2.2d
Hot-wire anemometer.

DOPPLER ANEMOMETERS

When sound or light is beamed into the atmosphere, any nonhomogenities in the air will reflect these beams. The resulting Doppler shift in the returning frequencies can be interpreted as an indication of wind velocity. The acoustic Doppler devices are more often used than the laser types. They are particularly useful in air pollution monitoring applications.

When laser-based Doppler anemometers are used, the intensity of the light scattered by the reflecting particles in the air is a function of their refractive index and the size (up to 5 microns). At particle sizes under 5 microns, it is safe to assume that the particle velocity is the same as that of the air (gas or liquid). Often, the naturally present particles (especially in water) will guarantee satisfactory performance, but, to obtain “perfect” measurements, seeding is recommended.

The operation of laser Doppler anemometers (LDAs) utilizes the Doppler effect or Doppler shift of frequency (color), which occurs as light is dispersed from the surface of moving particles. This shift in the frequency (color) of the light source (laser beam) 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), and thus it cannot be directly measured.

Therefore, an arrangement using the interference between the original and the refracted lights is used. This configuration is called the differential mode of the LDA. Figure 2.2e illustrates this principle, where beams from the laser source intersect each other in the measurement zone. In this zone, a set of interference plates are formed. When particles pass through these plates, they generate optical signals with flash frequencies equaling the Doppler frequency. This signal is then scanned by the photomultiplier and analyzed. The signal

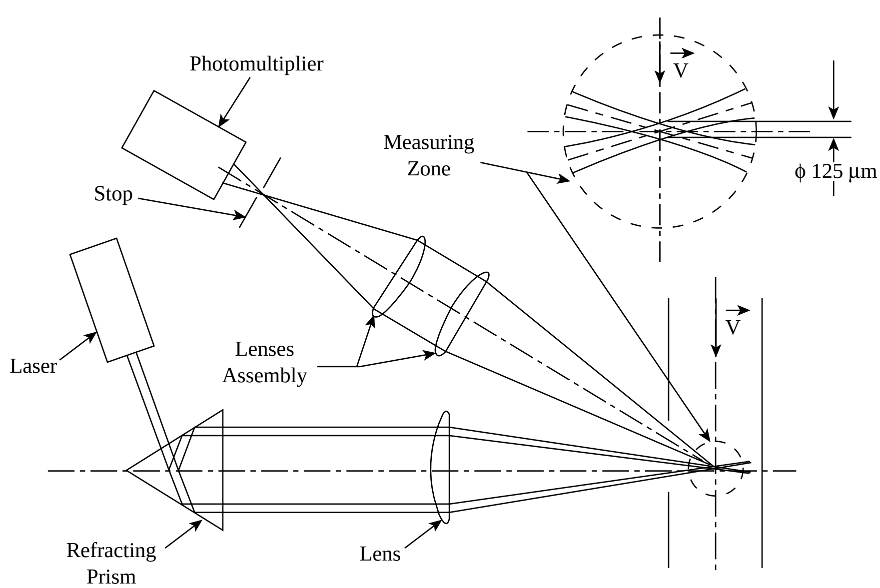


FIG. 2.2e
Operation of the laser Doppler anemometer.

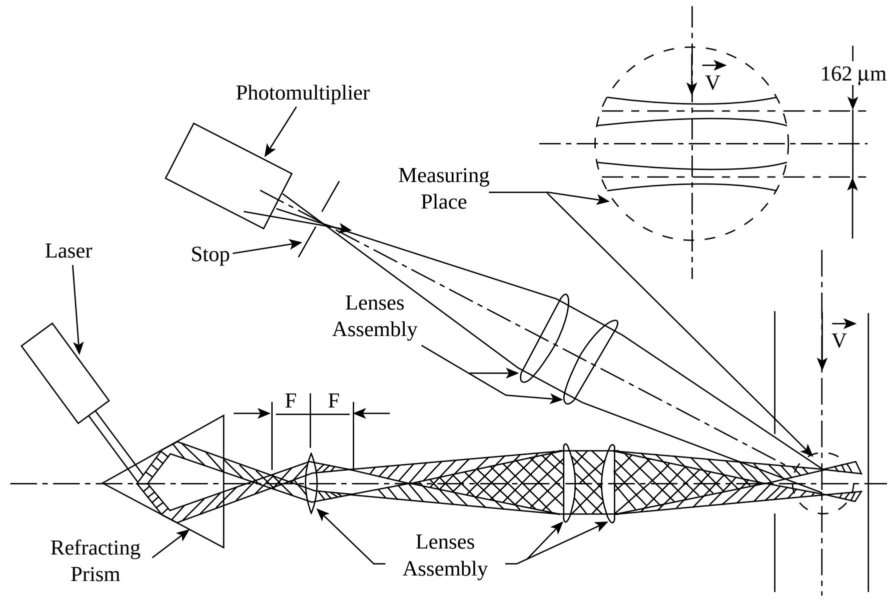


FIG. 2.2f
Operation of the laser two-focus anemometer.

has high frequency, several cycles, variable amplitude, and background noise.

In addition to the anemometers using the laser Doppler principle, there also are laser anemometers utilizing two-focus and transmit time principles. The laser two-focus anemometer (L2F) measures the time needed for particles to pass between the known distance between two focused beams (Figure 2.2f). The signal consists of two pulses and is scanned by a photomultiplier. The processing is provided by an autocorrelator. The disadvantage of this method is that the probability is small that the particles will pass through both beams. On the other hand, the resulting measurement signal is stronger and has less background noise.

Both types of noncontact Doppler measurements are suitable for nearly all hydrodynamic and aerodynamic velocity measurement applications.

CONCLUSION

For noncontacting velocity measurements, only the Doppler-type sensors can be considered. When locating other anemometers, the structures on which they are mounted are likely to disturb the airflow. A rectangular building will disturb airflow up to an elevation of about twice its height above grade, six times its height leeward, and twice its height in the windward direction.

In process industry installations, it is always a good idea to have wind direction indicators so the operators will always know which is the safe direction for escape in the event of a spill. Under such emergency circumstances, the knowledge of wind speed is of considerably less importance.

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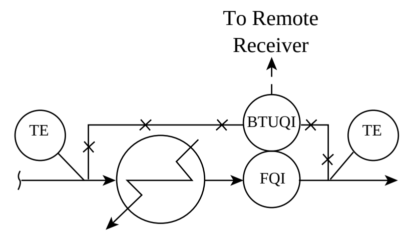
2.3 BTU Flowmeters for Heat Exchangers

B. G. LIPTÁK (1982, 1995, 2003)



Flow Sheet Symbol

BTU Flowmeter Types	A. All mechanical design B. Electronic BTU computer
Approximate Cost	A. About 50% more than the cost of the positive-displacement flowmeter; in smaller sizes and standard materials, usually less than $5000. B. The sum of the costs of a flow transmitter, a temperature-difference transmitter, multiplier, and display. The package cost varies with line size, materials of construction, transmitter accuracy, and type of display; it is likely to reach or exceed $10,000.
Inaccuracy	A. ±2 to 5% of full scale B. ±0.5% of full scale
Minimum ΔT	A. 5°F (2.8°C) B. 1°F (0.56°C)
Partial List of Suppliers	ABB Water Meters Inc., which bought Kent Meters Inc. (www.jerman.com/abbmeter.html) (A) Tyco Valves & Controls LP, which bought Hersey Measurement Co. (www.tycovalves.com) (A) Type "B" units can be configured by multiplying the output signal of any digital or analog flow transmitter with that of a temperature difference transmitter.

BTU flowmeters play a critical role in monitoring the energy flows and increasing energy efficiency in industry. The first step toward an energy-efficient plant design is a reliable energy audit throughout the plant. Such overall heat balance around the plant can be prepared only if the individual loads are accurately and separately measured.[1] This is illustrated in Figure 2.3a.

In the figure, the efficiency of the boiler is measured by the ratio of the total energy flows at points 1 and 2. This is usually done intermittently, by totalizing the fuel and steam flows over some period of time. The total energy input into the boiler is obtained by multiplying the total fuel consumed over that period with its heating value. The total useful energy output obtained from the boiler is obtained by multiplying the totalized steam flow by the difference between the enthalpy of the steam and the enthalpy of the feedwater. The ratio of these energy in and outputs is the boiler's actual efficiency.

Similarly, the coefficient of performance of the chiller shown in Figure 2.3a is measured by the ratio of the energy flows at points 10 and 11. Similarly, the efficiency of the

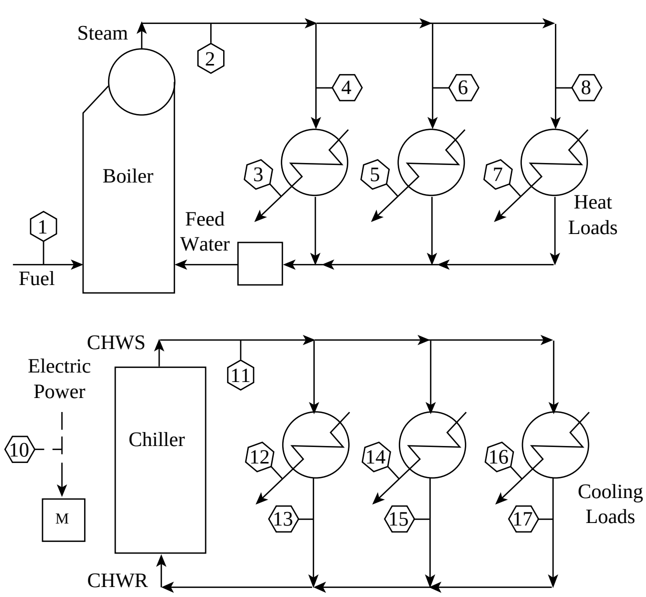


FIG. 2.3a
Plant-wide energy audit.

individual heat exchangers is also detected by measuring the energy flows on both the utility and the process sides of the exchanger, such as at points 3 and 4 or points 12 and 13 in Figure 2.3a.

The efficiency of the overall utility distribution system is determined by comparing the sum of the individual loads with the total supply at the source, such as comparing the energy flow at point 1 with the sum of energy flows 3, 5, and 7 or comparing 10 with the sum of 13, 15, and 17. The difference between the two represents the losses that occur as a result of phenomena such as insufficient thermal insulation of the pipe lines, leaking steam traps, and others.

When various techniques are considered for the optimization of the unit operations in a plant, it is recommended to empirically measure the energy consumption both before and after the optimization of the process. Without such reliable data, no accurate cost–benefit analysis can be made. The payback period for the installation is determined by dividing the optimization costs with the measured yearly energy saving.

For measuring most of the energy flows in Figure 2.3a, BTU flowmeters are required. These BTU computing units are available in both mechanical and electronic designs.

MECHANICAL BTU METERS

In mechanical BTU meters, flow is detected by positive-displacement or propeller-type sensors, and the volumetric flow rate is mechanically transmitted through gear trains. The temperature difference between the cold and hot sides of the exchanger is sensed by filled thermal bulbs, which are connected to a bourdon spring as illustrated in Figure 2.3b. Dual cam rollers are used in the computing mechanism so as to produce digital displays in both units of total BTUs and total flow.

The advantages of this design include its simplicity, low cost, and the fact that it does not require an external power supply. In centralized control systems, transmitting attachments can also be provided where remote readouts are needed.

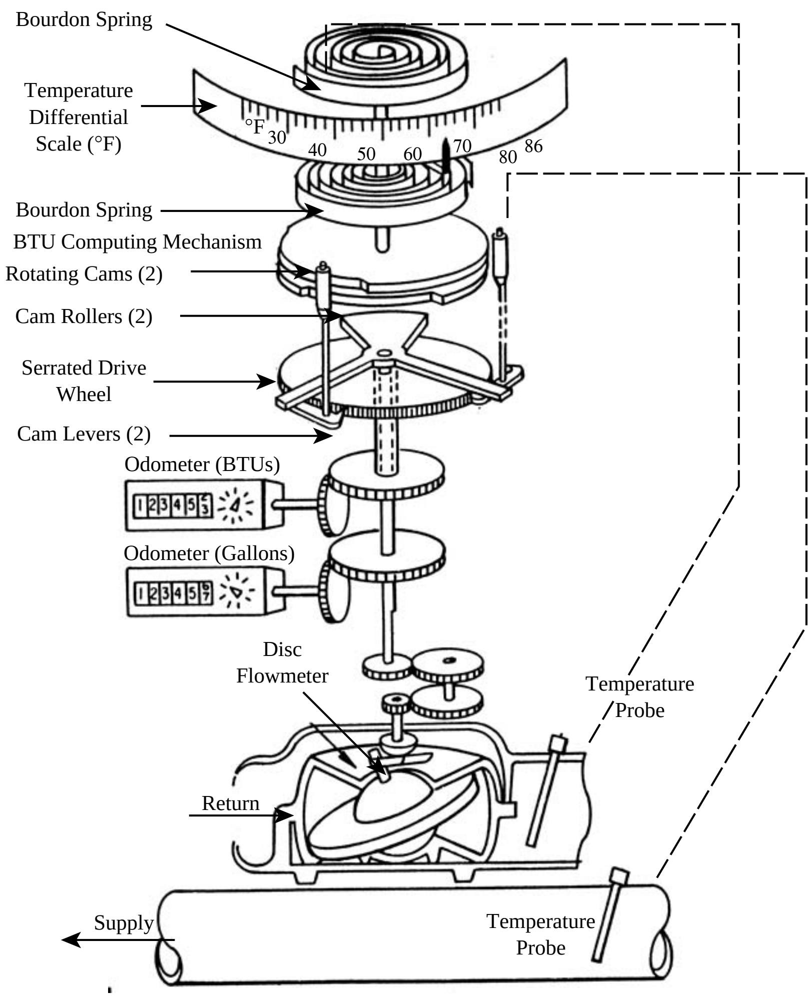


FIG. 2.3b
Mechanical BTU meter.

The limitations of this design include its relatively low accuracy, which is about ±2% of full scale, if the temperature difference exceeds 15°F (8.3°C). As the temperature difference decreases, this error rises and it becomes unacceptable at around 5°F (3°C). Therefore, these units are not recommended for use in applications where the temperature difference is under 5°F (3°C).

The typical applications for the mechanical BTU meters are in the heating, ventilating, and air conditioning (HVAC) industry and in heat exchanger efficiency monitoring.

ELECTRONIC BTU METERS

In electronic BTU computer packages, the flow sensor is usually a high-accuracy turbine flowmeter. The two temperatures or the temperature difference are usually detected by RTD-type temperature transmitters. Both the flow and temperature sensors are accurate devices, and they do provide high repeatability and wide turndown.

Therefore, the main advantage of electronic BTU computers is their superior accuracy. Their total error usually does not exceed ±0.5% of full scale.

As illustrated in Figure 2.3c, the BTU computer digitally displays the accumulated total ton-hours of refrigeration. In addition, analog electronic retransmission signals are also provided to facilitate the remote displays of flow rate, BTU rate, and temperature difference.

While these units are more expensive than mechanical BTU meters, the increase in cost can frequently be justified if the installation is larger or highly critical, or if accuracy is a prime concern.

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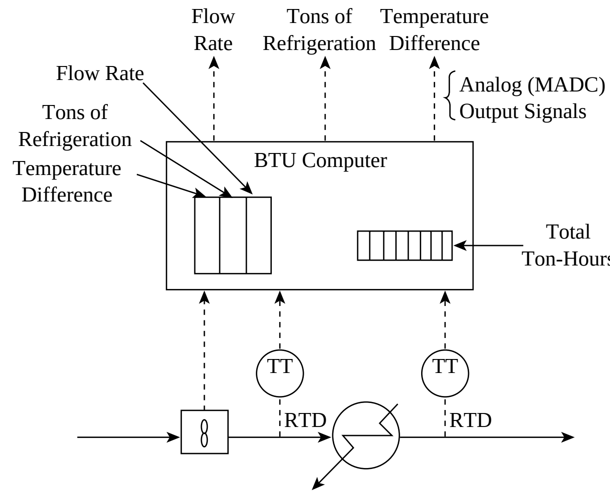

FIG. 2.3c
Electronic BTU meter.

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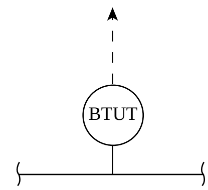
2.4 BTU Flowmeters for Gaseous Fuels

A. P. FOUNDOS (1982) **B. G. LIPTÁK** (1995, 2003)



Flow Sheet Symbol

Sensors Required	Conventional head-type flowmeter, calorimeter, or wobble index detector plus pressure and temperature measurements
Process Fluids	Gaseous fuels
Applications	Combustion processes are optimized by measuring and controlling fuel gas flow on the basis of the heat flow (BTU/h) requirement of the process
BTU Flow Range	From 100 BTU/min to very large heat flow rates; limited only by pipe sizes
Inaccuracy	±1.0 to ±2.0% of full scale, depending on the accuracy of the head type flowmeter used
Costs	Refer to Section 8.8 for the costs of the different types of calorimeters. The cost of a general-purpose wobble index detector is $10,000 to $12,000. Explosion-proof designs cost $5000 to $6000 more. For flow, temperature, and pressure transmitter costs, refer to Chapters 2, 4, and 5.
Partial List of Suppliers	ABB Process Automation—Analytical Div. (www.abb.com/us) The Foxboro Co. (www.foxboro.com) Honeywell Industrial Control (www.honeywell.com/acs/cp) ICS (www.icsadvent.com) Thermo Onix Process Analyzers (formerly Fluid Data/Amscor) (www.thermoonix.com).

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 wobble index sensors or calorimeters (discussed in Section 8.8). The burning of waste gases from a variety of process sources (Table 2.4a) and the accurate control of regular fuel gases made it necessary to measure their heat flows on line and continuously.

In the past, only the volumetric flow of the fuel gas was measured, and the heating value and the specific gravity of the gas were assumed to be constants. This approach is not acceptable for applications involving the burning of waste gases, because both their composition and heating values are variable.

In the past, in hazardous areas, the heating value of fuel gases could not be continuously measured, so specific gravity measurements were used to estimate their heating value and to control the combustion process. Today, continuous and explosion-proof calorimeters are available (Section 8.8) for the measurement of the heating value of any fuel gas. These optimized combustion controls are automatically adjusted for variations in either the specific gravity or the heating value of the fuel gas.

MEASURING HEAT FLOW BY WOBBLE INDEX

The heat flow rate (Q) of a gaseous fuel is calculated as the product of its volumetric flow rate at standard conditions (V_0) and of its calorific value (CV) or composition.

$$Q = V_0 \times CV = \text{SCF/hr} \times \text{BTU/SCF} = \text{BTU/hr} \qquad \textbf{2.4(1)}$$

Variations in composition affect both the heating value of the fuel gas and the pressure drop produced when the gas passes through an orifice plate. The volumetric flow through an orifice plate (V_0) can be expressed as the product of a constant (K) and the square root of the ratio $\Delta P/SG$. Therefore, the heat flow rate Q can be expressed as

$$Q = K\sqrt{\Delta P/SG} \times CV \qquad \textbf{2.4(2)}$$

where ΔP is the pressure differential across an orifice plate and SG is the specific gravity of the flowing fuel gas.

Rearranging that relationship for orifice pressure drop gives the following for $\sqrt{\Delta P}$:

$$\sqrt{\Delta P} = K \times V_0 \times \sqrt{SG} \qquad \textbf{2.4(3)}$$

TABLE 2.4a
Combustion Constants and Composition of Representative Manufactured and Natural Gases

	Blast Furnace Gas	*Coal Gas*	*Coke Oven Gas*	*Natural Gas Residual Follansbee, W. Va.*	*Natural Gas Sandusky, Ohio*	*SNG Green Springs, Ohio*	*LNG Columbia Gulf Coast*	*NG Columbia Gulf Coast*	*Refinery Gas*	*Producer Gas*
% Methane, CH_4		34.0	28.5		83.5	98.914	85.136	97.528	27.0	2.6
% Ethane, C_2H_6				79.4	12.5	0.01	10.199	1.238		
% Propane, C_3H_8				20.0			3.06	0.241		
% Ethylene, C_2H_4		6.6	2.9				0.0016		2.7	0.4
% Carbon monoxide CO	26.2	9.0	5.1			0.025			10.6	22.0
% Carbon dioxide, CO_2	13.0	1.1	1.4		0.2	0.439	0.018	0.487	2.8	5.7
% Hydrogen, H_2	3.2	47.0	57.4			0.61			53.5	10.5
% Nitrogen, N_2	57.6	2.3	4.2	0.6	3.8	0.002	0.201	0.224	3.4	58.8
% Oxygen, O_2			0.5				0.007			
% Other*							1.37	0.192		
BTU per cu. ft., high (gross) 60°F, 30 in. Hg, satd. H_2O	93	634	536	1868	1047				516	136
BTU per cu. ft., low (net) 60°F, 30 in. Hg, satd. H_2O	91.6	560	476	1711	946				461	128
Flame Temp. °F	2660	3910	3430	3830	3740				3970	3050

*Heavier hydrocarbons and traces of compounds including sulfurs.

The wobble index (*WI*) measures the ratio between the net calorific value (*CV*) and the square root of specific gravity (*SG*):

$$WI = CV/\sqrt{SG} \qquad \textbf{2.4(4)}$$

The advantage of detecting the wobble index is that it eliminates the need for separately measuring the specific gravity, because, as shown in Equation 2.4(5), the product of wobble index and orifice pressure drop [the product of Equations 2.4(3) and 2.4(4)] results in a value ($K \times Q$), which is directly related to the heat flow rate (Q), without requiring a separate measurement of SG.

$$WI \times \sqrt{\Delta P} = \left(CV/\sqrt{SG}\right) \times \left(K \times V_0 \times \sqrt{SG}\right)$$
$$= CV \times K \times V_0 = K \times Q \qquad \textbf{2.4(5)}$$

Because wobble index can be measured continuously in hazardous areas, this approach provides an on-line method of detecting heat flow rate.

THE BTU FLOWMETER LOOP

For gas fuels, the BTU flowmeter consists of a calorimeter (see Section 8.8) and an orifice type flow element. When the transmitted signals of these sensors are properly scaled, they can be multiplied to satisfy Equation 2.4(5) and the output of the multiplier (Figure 2.4b) represents the rate of heat flow in BTU/h units.

APPLICATIONS

In all combustion control processes, the calculation described in Figure 2.4b can provide a measurement signal that corresponds to the BTU flow rate. An optimized control system will ration the combustion air to this BTU flow rate in a feedforward configuration while responding to the firing rate demand signal of the process load in a feedback manner, as depicted in Figure 2.4c. This firing demand feedback signal to the setpoint of FIC-1 will throttle the fuel gas control value

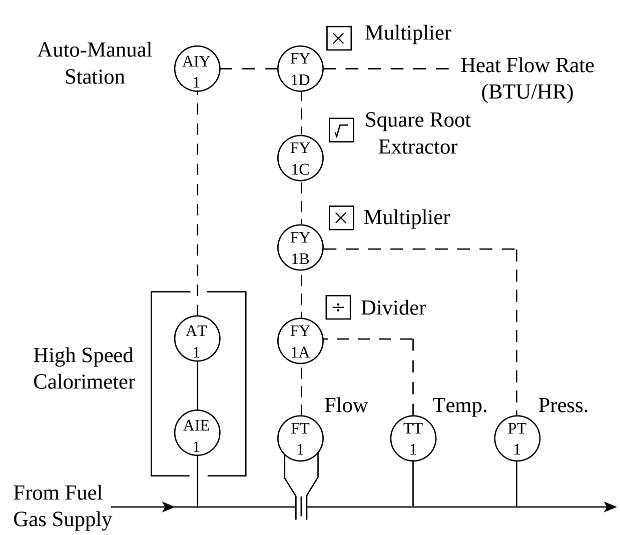


FIG. 2.4b
Heat flow rate detection loop.

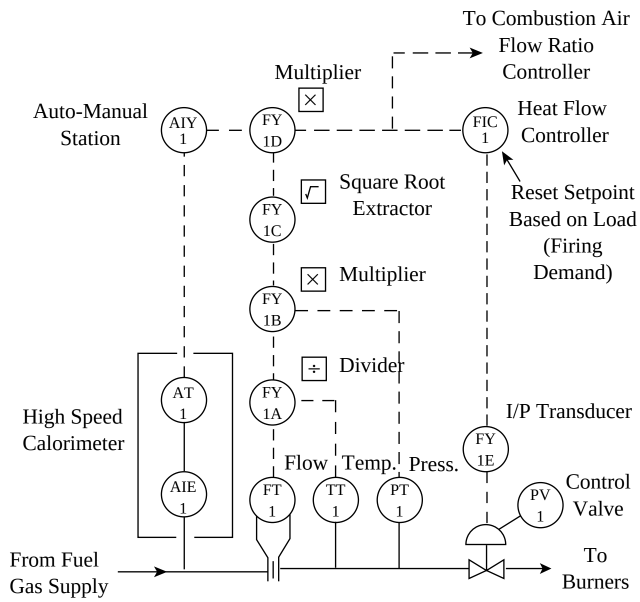


FIG. 2.4c
Combustion control system with heat flow controller.

(PV-1) until it delivers the BTU flow rate required. In conventional systems, only the volumetric flow rate of the fuel gas is maintained.

The configuration shown in Figure 2.4c is commonly used when combustion systems are optimized or plants are updated. This control system makes the control of multiple fuel boilers and furnaces much easier, because, by fixing the BTU flow rate of the gaseous fuel, it becomes feasible to modulate the liquid fuel(s) as a function of the excess air in the flue gas.

Another common application of BTU flow metering is the blending of an enriching or diluting gas into the fuels so as to control the BTU of the blend at a constant value. This constant BTU fuel gas can then be distributed throughout the plant to the various boilers, heaters, and gas-fired processes. In this case, the fuel gas BTU controller (AIC-1) becomes the cascade master of the makeup or diluent flow controller (FIC-1). Such a flow schematic of a typical blending control loop is shown in Figure 2.4d.

CONCLUSION

Using proven, available technology, a BTU flow rate loop can provide the control signal needed in such applications. In most combustion processes, the basic elements of such a control loop are an orifice flowmeter and a heating value detector that is fast enough to provide good response speed to process load variations.

Measuring the BTU flow rate provides a direct and accurate method of controlling and optimizing combustion processes.

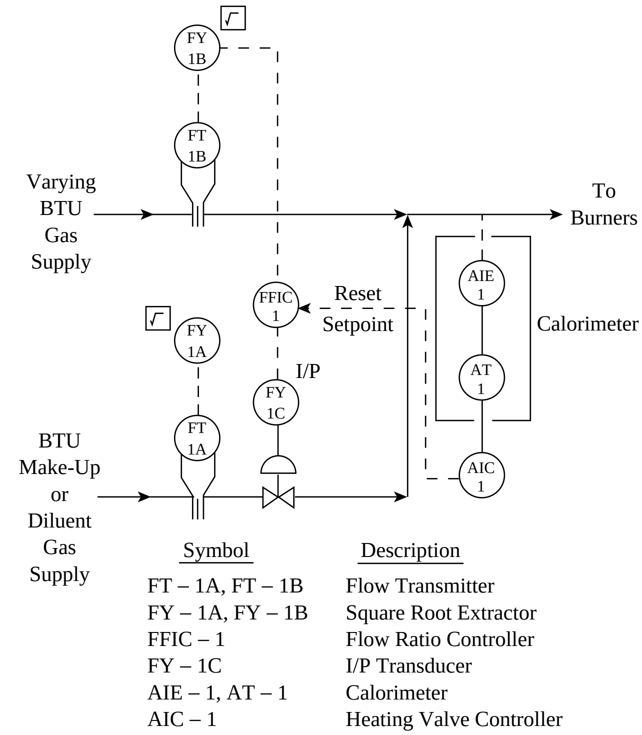


FIG. 2.4d
Control system to automatically maintain the heating value of mixed gas streams.

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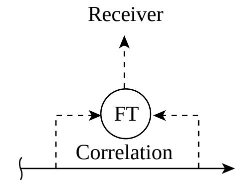
2.5 Cross-Correlation Flow Metering

B. G. LIPTÁK (1982, 1995) **H. M. HASHEMIAN** (2003)



Flow Sheet Symbol

Current Applications	Pumped paper pulp, pneumatically conveyed coal dust, cement, grain, plastic granules, chalk, water flow in nuclear and industrial plants, and animal foodstuffs
Sizes	Practically unlimited
Cost	A 4-in 150 # mass flowmeter with epoxy-resin-lined, enameled steel pipe costs $6000. If the sensor costs are not considered, the electronic detector alone is around $2000. Nuclear power plant flow metering installations range from $25,000 to $50,000.
Partial List of Suppliers	Analysis and Measurement Services Corp. (www.ams-corp.com) Endress+Hauser Inc. (www.us.endress.com) Kajaani Electronics Ltd. (Finland)

The oldest and simplest methods of flow measurement are the various tagging techniques. Here, a portion of the flowstream is tagged at some upstream point, and the flow rate is determined as a measurement of transit time. Variations of this technique include particle tracking, pulse tracking, and dye or chemical tracing, including radioactive types. The advantages of tagging techniques include the ability to measure the velocity of only one component in a multicomponent flowstream without requiring calibration or pipeline penetration. For example, electromagnetic tagging of gas-entrained particles allows for the determination of their speed through the detection of their time of passage between two points that are a fixed distance from each other.

Flow metering based on correlation techniques[1,2] is similar in concept to the tagging or tracing techniques, because it also detects transit time. As illustrated in Figure 2.5a, any measurable process variable that is noisy (displays localized variations in its value) can be used to build a correlation flowmeter. The only requirement is that the noise pattern must persist long enough to be seen by both detectors *A* and *B* as the flowing stream travels down the pipe. Flow velocity is obtained by dividing the distance (between the identical pair of detectors) by the transit time. In recent years, the required electronic computing hardware, with fast pattern recognition capability, has become available. Consequently, it is feasible to build on-line flowmeters using this technique.[3]

The following process variables display persistent enough noise patterns (or local fluctuations) that correlation flowmeters can be built by using an identical pair of these sensors:

Density
Pressure
Temperature
Ultrasonics
Gamma radiation
Capacitive density
Conductivity

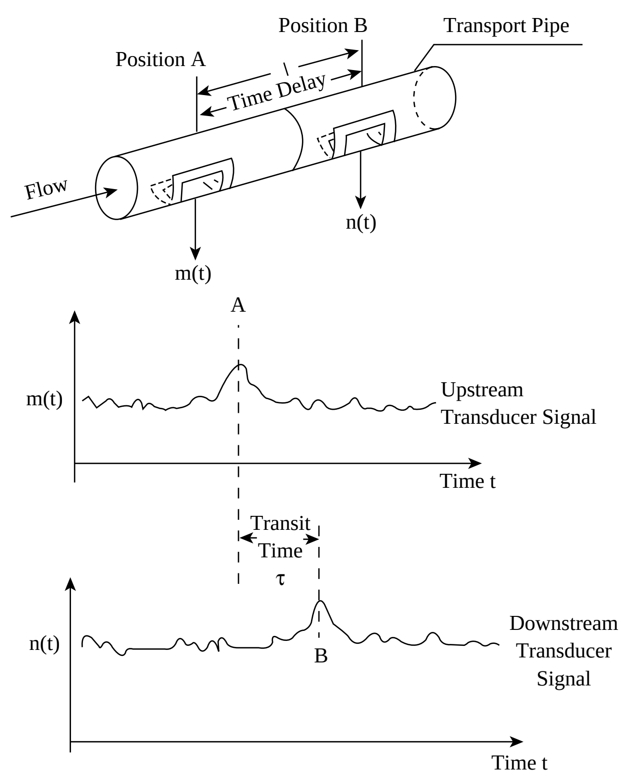


FIG. 2.5a
Cross-correlation flow metering.

Several of the above process variables (such as temperature,[4,5] gamma radiation, and capacitive density[6]) have been investigated as potential sensors for correlation flowmeters. One instrument has been developed that uses the principle of ultrasonic cross-correlation to measure heavy-water flow.[3] Others are available for paper pulp applications using photometric sensors and for solids flow measurement utilizing capacitance detectors (Figure 2.23v). For cross-correlation flowmeters applied in solids flow applications, refer to Section 2.23.

When fully developed, correlation flow metering can extend the ability to measure flow not only into the most hostile process environments but also into areas of multiphase flow and into three-dimensional flow vectoring.

NUCLEAR POWER PLANT APPLICATIONS

Most process variables fluctuate, so the outputs of most process sensors undergo variations in their output. These variations can also be exploited to obtain cross-correlation flow sensors. More specifically, process sensors that normally measure temperature, pressure, radiation, or other process variables can also be used to determine the velocity of fluid flow. This can be done passively by recording the sensor output for a period of time and extracting the fluctuating component of the output (called the AC signal). If a pair of sensors are installed in the same pipe at a known distance from each other, flow velocity can be obtained by cross-correlating the two AC signals from these two sensors. Once the fluid flow velocity is determined, the volumetric or mass flow rate can be calculated on the basis of the physical dimensions of the process piping and the properties of the fluid.

Determining the Transit Time

The principle of cross-correlation flow measurement is illustrated in Figure 2.5b, where a pipe is shown with two sensors installed some distance apart. Also shown in Figure 2.5b are the AC outputs of these two sensors. The output of one sensor is represented by $x(t)$, and the output of the other sensor is represented by $y(t)$. These output signals may be cross-correlated to identify the *transit time* between the two sensors. The transit time is the time required for the process fluid to travel between the two sensors. To obtain the fluid flow velocity, the transit time has to be divided by the distance between the two sensors.

To cross-correlate the outputs of two sensors, first the two output signals are multiplied by each other, after which the second signal is slowly shifted, a little bit at a time, toward the first signal until the two signals are superimposed. The averaged product of the two signals is then plotted as a function of the time shift. This plot will normally peak at a time that is equal to the transit time, as illustrated in Figure 2.5c.

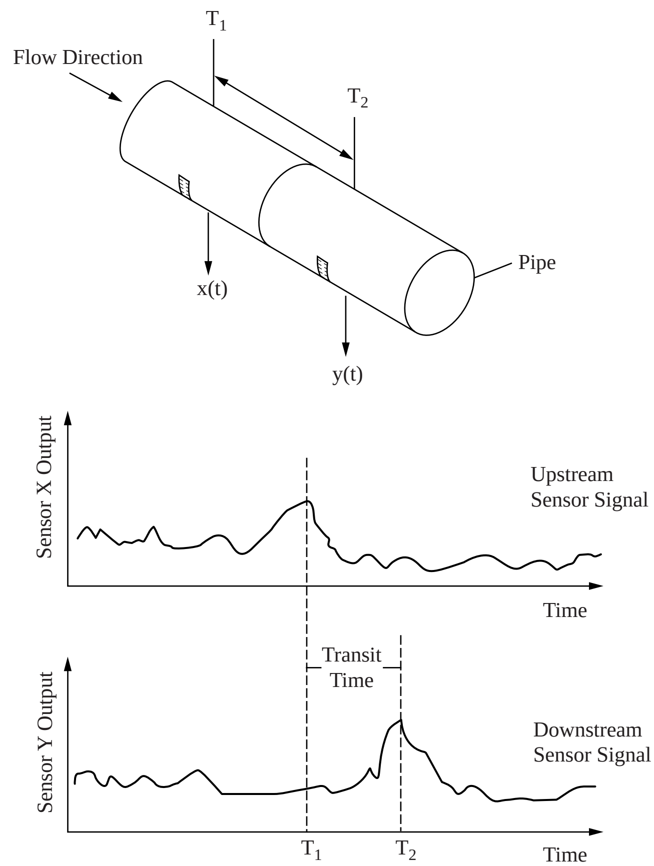


FIG. 2.5b
Illustration of principle of cross-correlation flow monitoring.

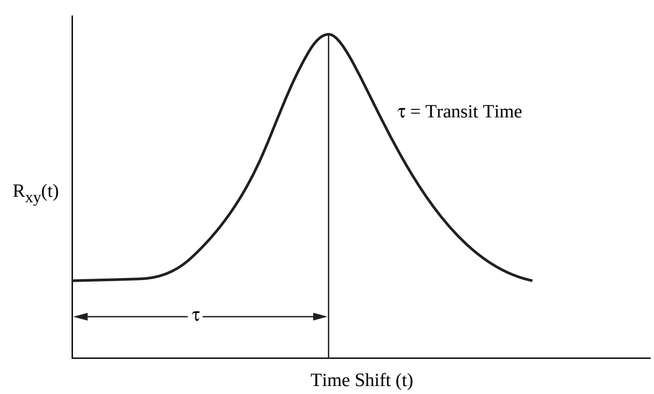


FIG. 2.5c
Cross-correlation plot and illustration of transit time.

The cross-correlation function (R_{xy}) for the signals $x(t)$ and $y(t)$ is given by the following equation:

$$R_{xy}(t) = \int x(z)y(t+z)dz \qquad \textbf{2.5(1)}$$

In this equation, t is the time interval that one signal is shifted toward the other, and z is the integration variable.

The cross-correlation function, R_{xy}, will normally have values between +1.0 and −1.0, provided that x and y are constructed from mean-removed raw signals divided by their standard deviations. Values close to +1.0 indicate a good direct correlation between two signals, and values close to −1.0 indicate a good inverse correlation. Conversely, when there is little or no correlation between the two signals, the value of R_{xy}, will approach zero.

The transit time can also be obtained from plotting the phase between the two signals as a function of frequency. For this, the slope of the phase as a function of frequency is used to calculate the transit time as follows:

$$2\pi\Delta F\tau = \Delta\phi$$

$$\tau = \frac{\Delta\phi}{2\pi\Delta F} = \frac{\text{slope (Degrees/Hz)}}{\text{360 (Degrees)}} \qquad \textbf{2.5(2)}$$

where

τ = transit time (sec)
$\Delta\varphi$ = change in FFT phase (degrees)
ΔF = frequency band of highest coherence (Hz or $\sec^{-1}$) over which $\Delta\phi$ occurs
2π (radians) = 360°

To eliminate the effects of process variations that are not related to flow, the slope is calculated over the region of the phase spectrum where the two signals are most coherent. Figure 2.5d shows a phase vs. frequency plot and the calculation of the transit time. As shown by Equation 2.5(2) and Figure 2.5d, the transit time is calculated by dividing the slope of the phase plot by 360°.

Reliability and Accuracy

The reliability of cross-correlation flow metering is improved if

1. The response times of the two sensors are similar and fast compared to the spectrum of the process and the transit time that must be resolved.
2. The correlation between the data does not occur at or after the break frequency of the sensor and/or the data acquisition system.
3. The information being correlated can be resolved from the effects of other process perturbations and noise.

In theory, any two sensors can be used to provide signals for cross-correlation flow measurements as long as the two sensors can register a process parameter that affects the output of both sensors. For example, signals from two temperature sensors (thermocouples, RTDs, and so forth) or two pressure sensors can be cross-correlated to determine fluid flow rate. Figure 2.5e shows a phase plot for two RTDs. This

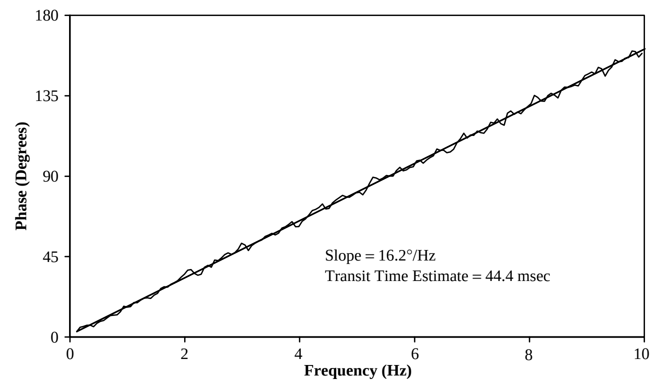


FIG. 2.5d
Phase plot and calculation of transit time.

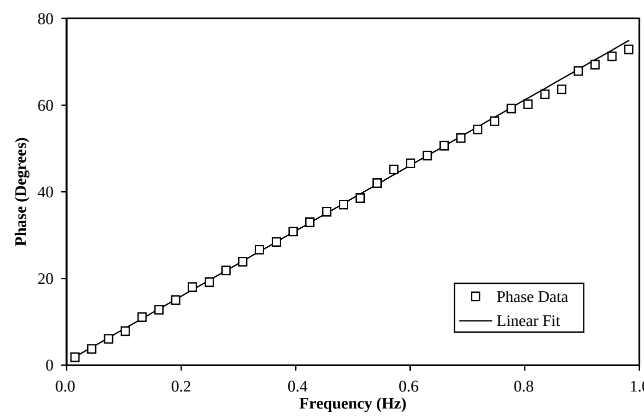


FIG. 2.5e
Cross-correlation phase plot for a pair of RTDs.

information was generated in a laboratory test loop where cross-correlation flow equipment and techniques were developed and validated. The plot shows the experimental data as well as the least-squares fit to the data. The least-squares fit provides the slope of the line that is then divided by 360° to obtain the transit time. Based on these laboratory experiments, it has been determined that the error in cross-correlation-based flow measurement is less than 3%.

Even dissimilar sensors, such as a temperature and a pressure detector, can be used for cross-correlation flow measurement if the temperature and pressure measurements are related.

Nuclear Power Applications

The cross-correlation technique of flow metering has been used successfully in nuclear power plants by using the thermal hydraulic fluctuations within the reactor coolant system, which are detectable by temperature, pressure, and radiation sensors. For example, the signals from temperature and neutron detectors have been cross-correlated to monitor the

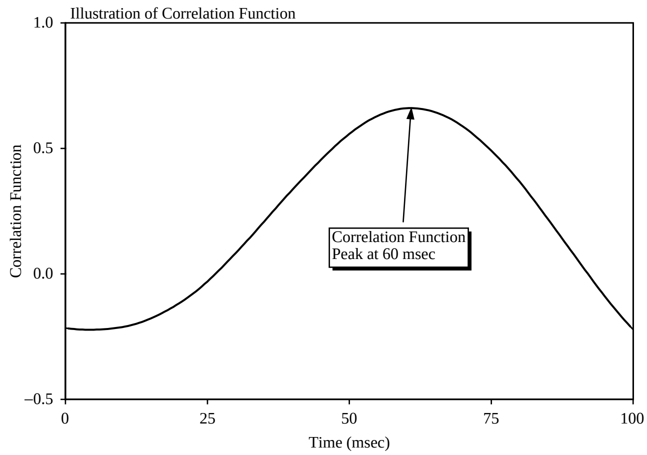


FIG. 2.5f
Plot of correlation function for a pair of signals from a thermocouple and a neutron detector.

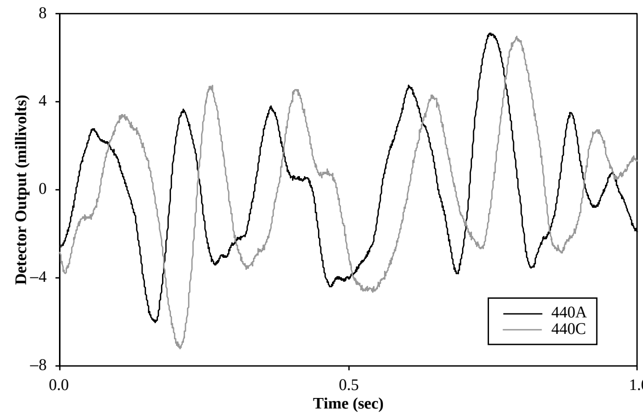


FIG. 2.5g
Examples of raw data for a pair of sensors used for cross-correlation flow measurements.

flow through the core. Figure 2.5f shows a cross-correlation plot for a thermocouple that is installed on top of the reactor core inside a pressurized water reactor (PWR) and a neutron detector located outside the reactor at a lower elevation than the thermocouple. This method is not normally used for flow measurements in nuclear power plants. Rather, it is used for monitoring flow rate changes and for detecting flow blockages within the reactor coolant system.

A more direct means of flow measurements in PWR plants is to cross-correlate the signals from a pair of nitrogen 16 (N-16) radiation detectors that are installed on the reactor coolant pipes. The N-16 detectors measure the gamma radiation produced in the reactor water by the neutron bombardment of oxygen-16. When oxygen-16 is bombarded by fast neutrons, an unstable isotope of nitrogen is produced, which is N-16. It decays rapidly while emitting gamma radiation. Even though it decays rapidly, N-16 activity lasts long enough to measure the gamma radiation as the water circulates in the reactor coolant loop. This method of flow measurement is often referred to as *transit-time flow measurement (TTFM)*. Figure 2.5g shows two raw data records for a pair of N-16 detectors in a PWR plant.

Data accumulated for a period of only one second is shown, although data can be collected for periods of 1 or 2 h if high measurement accuracy is desired. If the purpose of the measurement is only to detect sudden flow changes or blockages, then shorter data recording periods are adequate.

The TTFM System

The TTFM system (Figure 2.5h) includes a signal conditioning circuit shown in Figure 2.5h. This circuitry is used to extract the AC signals that are cross-correlated for flow measurement. The raw signal typically contains a DC component on which the AC signal of interest is superimposed.

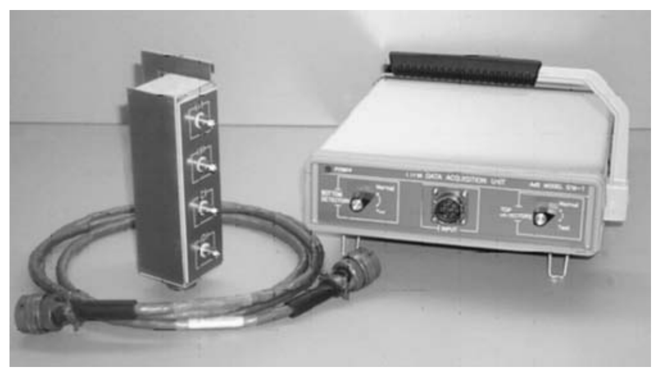


FIG. 2.5h
Photograph of TTFM system. (Courtesy of Analysis and Measurement Services Corp. [AMS].)

As shown in Figure 2.5i, the DC component of each signal is removed by a highpass filter or by a bias that is added to or subtracted from the signal. The remaining component (the AC signal) is then amplified and sent through a lowpass filter to remove the extraneous noise and to provide for anti-aliasing. A computer with a built-in analog-to-digital converter (A/D) then samples the signals and performs the cross-correlation to identify the transit time and calculate the flow. Typically, the cross-correlation analysis is performed in both the time domain, using the cross-correlation plot, and in the frequency domain, using the phase plot, and the results are averaged to provide the fluid flow velocity.

The TTFM software not only collects the data, it performs data qualification and statistical analysis to ensure that the signals are suitable for analysis, the sensors have comparable response times, and the cross-correlated AC signals have the required statistical and spectral properties. Figure 2.5j shows a block diagram of the entire TTFM system.

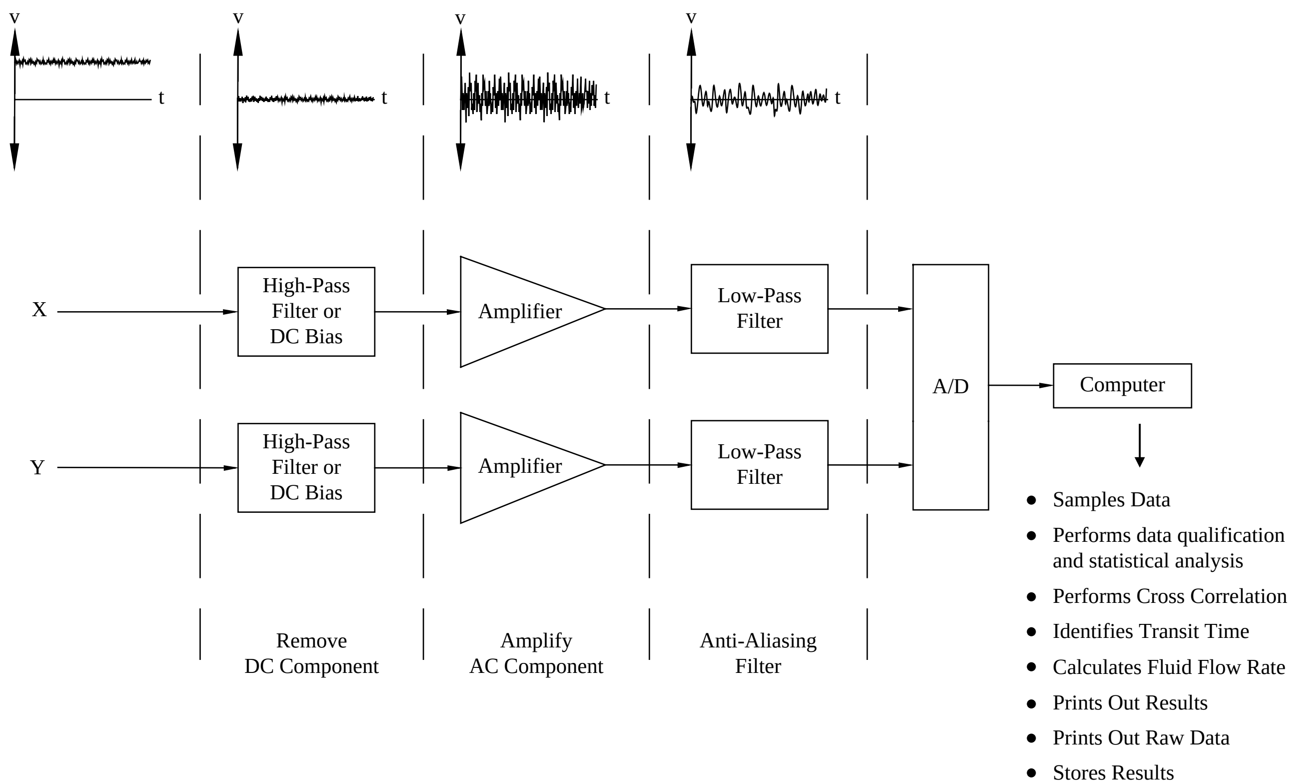


FIG. 2.5i
Block diagram of data acquisition system of TTFM.

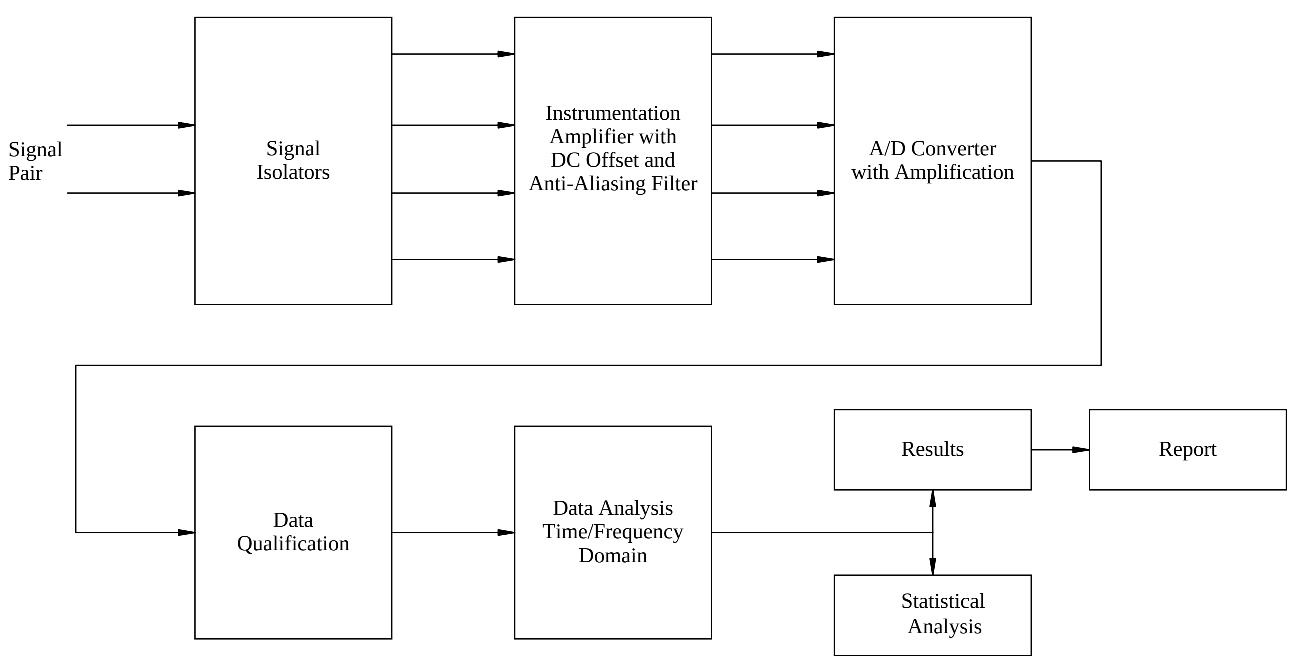


FIG. 2.5j
Block diagram of TTFM system.

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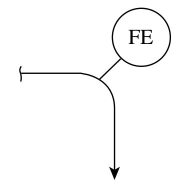
2.6 Elbow Taps



W. H. HOWE (1969) **B. G. LIPTÁK** (1982, 1995) **I. H. GIBSON** (2003)

Design Pressure	Limited by piping design class only
Operating Temperature Range	–330 to +1100°F (–200 to +600°C)
Fluids	Liquids, vapors, or gases
Differential Pressure	0- to 10-in water column (0 to 2.5 kPa)
Sizes	0.5 to 20 in (12 to 500 mm)
Inaccuracy	±2 to ±10% FS
Cost	Approximately $1000 plus value of elbow and measuring device (usually a differential-pressure transmitter)
Partial List of Suppliers	Normally fabricated on site

Flow measurement using elbow taps depends on the detection of the differential pressure developed by centrifugal force as the direction of fluid flow changes in a pipe elbow. Taps are located on the inner and outer radii in the plane of the elbow. The pressure taps are located at either 45° or 22.5° from the inlet face of the elbow (Figure 2.6a).

A SIMPLE FLOWMETER

Elbow taps are easy to implement, because most piping configurations already contain elbows in which taps can be located. This guarantees an economical installation and results in no added pressure loss. The measurement introduces no obstructions in the line. Accumulation of extraneous material in the differential-pressure connections can plug the elbow taps. Therefore, they should be purged if the process fluid is not clean.

As is the case with other head-type primary flow measurement devices, the differential pressure developed by a given flow is precisely repeatable. However, the flow coefficient of an elbow tap calculated from the physical dimensions of the pipe is generally considered reliable to only ±5 to ±10%. This is quite satisfactory for many flow control applications where repeatability is the primary consideration. If absolute accuracy is desired, a more precise flowmeter should be used, or the elbow tap readings should be calibrated, preferably in place and using the working fluid. Not enough data exist to establish precise correction factors for effects of upstream disturbances, viscosity, and roughness in pipe and elbow surfaces, and no published standards are available.

Elbow taps develop relatively low differential pressures. For this reason, they cannot be used for measurement of low-velocity streams. Typically, water flowing at an average velocity of 5 ft/sec (1.5 m/sec), roughly 200 GPM in a 4-in. pipe (45 m^3/h in a 100-mm pipe) through a "short-radius" elbow with a centerline radius equal to the pipe diameter develops about 10 in. of water differential pressure (2.5 kPa). This is approximately the minimum full scale value recommended for reliable measurement. Taps in long radius pipe or tube bends do not develop sufficient differential pressure for good flow measurement at low flow velocities.

In comparison with an elbow installation, an orifice will generate a head (1.4 to 2.2) $(1-\beta^4)/\beta^4$ higher at the same flow rate. For example, for $\beta = 0.65$, the orifice head developed will be approximately 6.5 times that of a short-radius elbow.

LOCATION AND SIZE OF TAPS

The upstream piping is a factor in the installation of elbow taps. It is recommended to provide at least 25 pipe diameters of straight pipe upstream and 10 diameters downstream. The tap holes should be perpendicular to the surface of the elbow and slightly rounded at the pipe surface, with no burrs

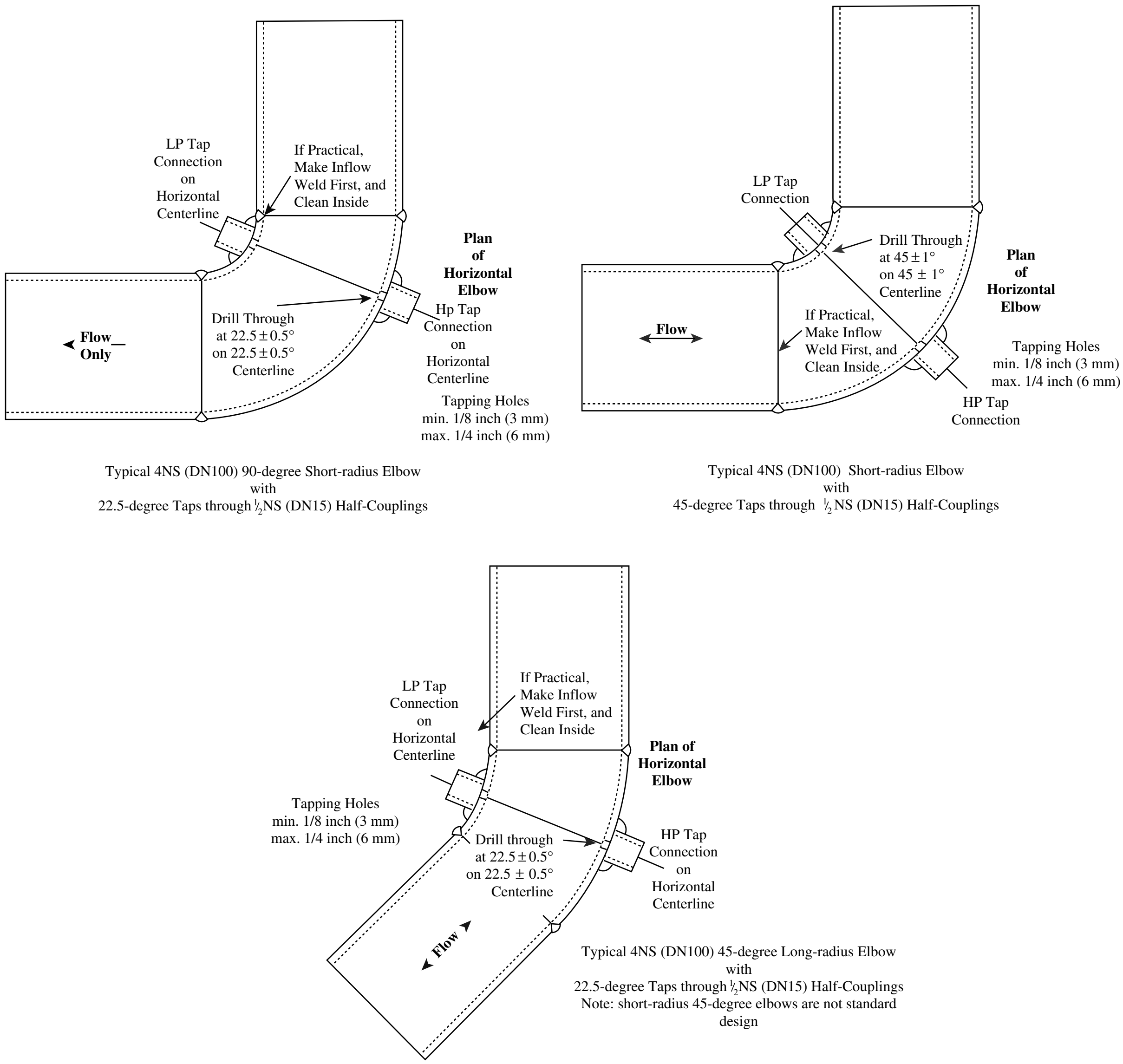


FIG. 2.6a
Alternate tap locations in elbow flowmeter designs.

or protrusions. Jig setting the tap connections using a rod across the elbow to ensure a common axis is recommended.

Tap hole diameter should not exceed 0.125 of the pipe diameter. Elbows may be flanged with the elbow diameter equal to the pipe diameter or, more commonly, welded. With a welded installation, it is preferable to make the upstream weld first, because this permits access to clean up the more critical upstream joint.

An elbow of smaller diameter than the pipe, with a reducer between pipe and elbow, has the advantage of higher differential for a given flow. Threaded elbows with the flow section larger than the pipe develop less differential pressure and thereby increase the error.

The flow coefficient of a pipe elbow can be reliably determined only if the inside surface of the elbow is smooth. The elbow should be precisely aligned with the pipe, making sure that no gaskets or weld metal are protruding into the flowing stream either at the inlet or outlet of the elbow.

When selecting an existing elbow for flow measurement purposes, it is preferable to pick one that is located between two horizontal pipe sections. This will guarantee that the pressure taps will be horizontal, and material will not accumulate in them. If the elbow were located between a horizontal and a vertical pipe section, the pressure tap on the inner radius would slope upward, and the one on the outer radius would slope downward.

As the differential-pressure instrument is piped to these taps, this piping will not be self-draining. The high and low points in the connecting piping will tend to trap either the vapors on liquid services or the liquid condensate on vapor services. As the total pressure differential to be measured is already low, this interference can make the installation unsatisfactory.

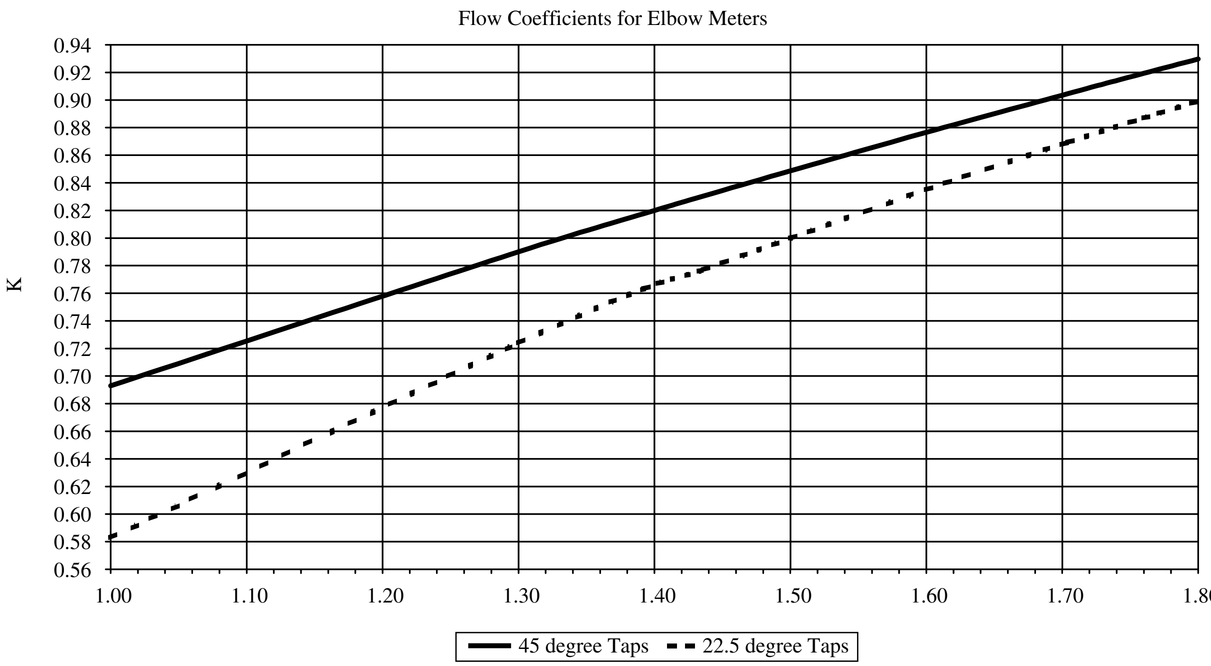


FIG. 2.6b
Elbow flowmeter flow coefficients.

Some tests suggest that the 22.5° tap locations provide more stable and reliable readings and are less affected by upstream pipe configuration. They also give 7 to 15% higher differential than the 45° values. Spink[5] gives a set of correlated experimental data for both 45° and 22.5° measurements. The 22.5° data in Figure 2.6b is adapted from this information.

For 45° tap orientation, the flow coefficient (K) is given by Murdock[1,2] as

$$K = \sqrt{\frac{r_b}{2D}} + \frac{6.5\sqrt{\frac{r_b}{2D}}}{\sqrt{\mathrm{Re}_D}} = \sqrt{\frac{r_b}{2D}} * \left(1 + \frac{6.5}{\sqrt{\mathrm{Re}_D}}\right) \pm 4\% \qquad \textbf{2.6(1)}$$

using consistent units, where the pipe Reynolds number (Re_D) is greater than 10^4 and $r_b/D > 1.25$. Note that, for short-radius elbows, this ratio is 1.0, and hence outside the limit, r_b, is the centerline radius of the elbow, and D is the actual bore of the elbow, measured in four planes and averaged.

The second term is 6.5% at the minimum Reynolds number of 10^4 and negligible above 10^6. Later work by Murdock[3] suggests a slightly lower value,

$$K = 0.98\sqrt{\frac{r_b}{2D}} \pm 6\% \text{ for Reynolds number above } 10^5 \qquad \textbf{2.6(2)}$$

Units

Symbols used are consistent with ISO 5167.

C	Discharge coefficient in orifice equations
D	Pipe diameter (at plane of elbow tappings)
K	Discharge coefficient term for elbow
p_{f1}	Absolute pressure upstream of elbow
p_{lp}	Absolute pressure at inner tapping of elbow
p_{hp}	Absolute pressure at outer tapping of elbow
q_m	Mass flow rate
r_b	Radius of curvature of elbow at centerline
Re_D	Reynolds number referred to D
ε	Expansion factor (in U.S. standards, Y)
ρ	Density
$_1$(subscript 1)	Upstream conditions

The factor K replaces the term $C/\sqrt{1-\beta^4}$, and D replaces d in the standard orifice equations (see Section 2.15).

$$q_m = \frac{C}{\sqrt{1-\beta^4}}\varepsilon_1 \frac{\pi}{4} d^2 \sqrt{2\Delta p \rho_1} \quad \text{to give}$$
$$q_m = K\varepsilon_1 \frac{\pi}{4} D^2 \sqrt{2(p_{hp} - p_{lp})\rho_1} \qquad \textbf{2.6(3)}$$

For gas flow, the gas expansion factor has not been heavily studied; a single set of data on air suggests $\varepsilon = 1 + 1.3((p_{hp} - p_{lp})/p_{f_1})^2$ where the pressure measurements are in consistent units.

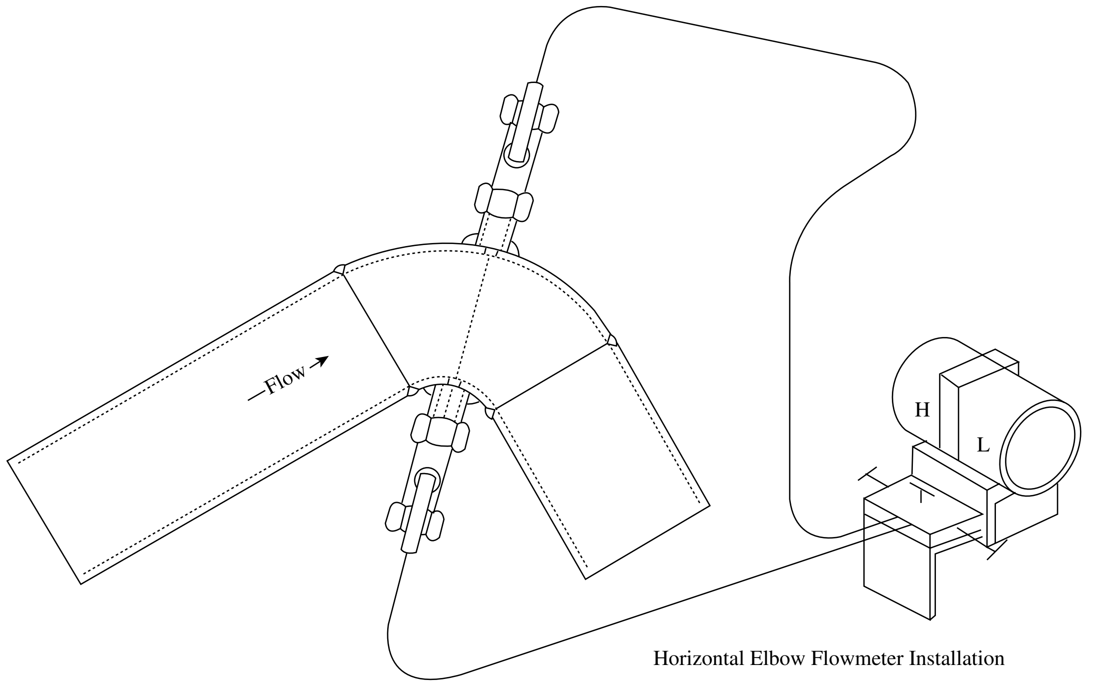


FIG. 2.6c
Horizontal elbow flowmeter installation.

The pressure differential term is so small that $\varepsilon = 1$ is within the normal limits of error in many cases. The coefficient values for 22.5° taps are quoted by Spink.

For an elbow tap installation, complete with d/p transmitter and three-valve manifold, refer to Figure 2.6c.

OTHER d/p-PRODUCING ELEMENTS

In addition to elbow taps, the differential pressure produced by centrifugal forces can also be converted into flow readings by other configurations. These include the Winter-Kennedy taps installed in the scroll case of hydraulic turbines. Another design is the full-circle loop with taps located at the midpoint of the loop. It is claimed that this design provides high accuracy and minimum sensitivity to upstream piping configuration.

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3. Murdock, J. W., Foltz, C. J. and Gregory, C., *J. Basic Eng.,* 86, 498–506, 1964.
4. Miller, R.W., *Flow Measurement Engineering Handbook,* 3rd ed., McGraw-Hill, New York, 1996.
5. Spink, L. K., *Principles and Practice of Flow Engineering*, 9th ed., The Foxboro Co., Invensys Systems, Inc., Foxboro, MA, 1967.

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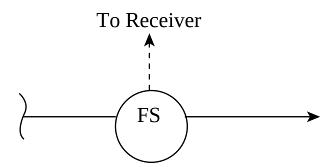
2.7 Flow Switches

B. G. LIPTÁK (1982, 1995) **W. H. BOYES** (2003)



Types of Designs

A. Bypass or differential-pressure
B. Capacitance or RF inductance
C. Hot wire anemometer
D. Paddle, vane, or rotor
E. Thermal
F. Ultrasonic (including Doppler)
G. Valve body
H. Variable area or piston
I. Microwave
J. Surface charge

Types of Services

0. Liquids (flow or no-flow)
1. Liquids (adjustable high- or low-flow)
2. Gases, vapors (adjustable high- or low-flow)
3. Solids (flow/no-flow, some adjustable)

Costs

Small oil, air, and water switches (types A and D) can be obtained for $50 to $150; paddle-type flow switches for air ducts cost $150, and for water service through 1-in (25-mm) NPT fitting and stainless-steel construction, $375; types B, E, and H units range from $150 to $800 in small sizes and standard materials; types C and F start at approximately $500 and range to over $1000; solids flow switch types I and J cost around $1000; Type G in 1-in (25-mm) size and bronze construction is $120, in stainless steel $400; a 2-in (50-mm) unit in these materials is $300 and $600, respectively.

Partial List of Suppliers

A. Bypass or differential-pressure
Meriam Instrument (www.meriam.com) (A-1, 2)
Mid-West Instrument (www.midwestinstrument.com) (A-1, 2)
W.E. Anderson Div. of Dwyer (www.dwyer-inst.com) (A-2, D-1)
CTE Chem Tec (www.chemtec.com) (A-0, 1, 2)

B. Capacitance or RF inductance
ABB Instrumentation (www.abb.com) (B-3)
Babbitt International Inc. (www.babbittlevel.com) (B-3)
Delta Controls Corp. (www.deltacnt.com) (B-0, D-1)
Endress+Hauser Inc. (www.us.endress.com) (B-0, F-3)
Magnetrol International (www.magnetrol.com) (B-0)
Princo Instruments Inc. (www.princoinstruments.com) (B-1, 3)
Robbins and Myers Inc., Moyno Div. (www.moyno.com) (B-0)
SOR Inc. (www.sorinc.com) (B, D, H-1)

C. Hot wire anemometer
Kurz Instruments Inc. (www.kurzinstruments.com) (C-2)
TSI Inc. (www.tsi.com) (C-2)
JLC International (www.jlcinternational.com) (C-2)

D. Paddle, vane, or rotor
Delta Controls Corp. (www.deltacnt.com) (B-0, D-1)
W.E. Anderson Div. of Dwyer (www.dwyer-inst.com) (A-2, D-1)
Aqualarm (www.jam.uk.com) (D-1)
CTE Chem Tec Equipment Co. (www.chemtec.com) (D-1, 2)

Custom Services (D-0)
H.G. Dietz Co. (D-1, 2)
Gems Sensors Inc. (www.gemssensors.com) (D-1, 2)
Harwil Corp. (www.harwil.com) (D-1)
Proteus Industries Inc. (www.proteusind.com) (D-1)
Revere Transducers (www.reveretransducers.com) (D-1)
Kobold Instruments Inc. (www.koboldusa.com) (D-1, 2)
Johnson Controls (www.johnsoncontrols.com) (D-1, 2)
Oilgear Co. (www.oilgear.com) (D-1)
Omega Engineering Inc. (www.omega.com) (D, F, H-1, 2)
OPW Div. of Dover Corp. (www.opw-fc.com) (D-1)
SOR Inc. (www.sorinc.com) (B, D, H-1)
Universal Flow Monitors Inc. (www.flowmeter.com) (D, H-1)
Bindicator Div. of Venture Meas. (www.bindicator.com) (D-3)
Magnetrol International (www.magnetrol.com) (D-1, 2)
Lake Monitors (www.lakemonitors.com) (D-0, 1)
George Fischer Signet (www.gfsignet.com) (D-0, 1)

E. Thermal
Delta M Corp. (www.deltam.com) (E-1, 2)
Hydril Co. (www.hydril.com) (E-0)
E-T-A Control Instruments (www.etacbe.com) (E-1, 2)
FCI Fluid Components Inc. (www.fluidcomponents.com) (E-1, 2)
Intek Inc. (www.intekflow.com) (E-1, 2)
Turck Inc. (www.turck-usa.com) (E-0, 1)
McMillan Co. (www.mcmillancompany.com) (E-0, 1)
IFM Efector (www.ifmefector.com) (E-0, 1)
Magnetrol International (www.magnetrol.com) (E-0, 1)
Eldridge Products Inc. (www.epiflow.com) (E-0, 1, 2)
Sierra Instruments Inc. (www.sierrainstruments.com) (E-0, 1, 2)
Kurz Instruments (www.kurzinstruments.com) (E-0, 1, 2)

F. Ultrasonic (including Doppler)
Brooks Instrument Div. of Emerson (www.emersonprocess.com) (F-1, H-1, 2)
Cosense Inc. (www.cosense.com) (F-0)
Endress+Hauser Inc. (www.us.endress.com) (B-0, F-3)
Thermo MeasureTech (www.thermomeasuretech.com) (F-1, 3)
Omega Engineering Inc. (www.omega.com) (D, F, H-1, 2)
Zi-Tec Instrument Corp. (F-1, 2)
Magnetrol International (www.magnetrol.com) (F-3)
Controlotron Corp. (www.controlotron.com) (F-0, 1)

G. Valve body
Hedland Inc. (www.hedland.com) (G-1, 2)
Magnetrol International (www.magnetrol.com) (G-1)
Malema Inc. (www.malema.com) (H-0, 1)
ERDCO Engineering Corp. (www.erdco.com) (H-0, 1)
Lake Monitors (www.lakemonitors.com) (G-1, 2)
CTE Chem Tec (www.chemtec.com) (G-0, 1, 2)

H. Variable area or piston
Brooks Instrument Div. of Emerson (www.emersonprocess.com) (F-1, H-1, 2)
ABB Instrumentation (www.abb.com) (H-1, 2)
Flow & Level Controls (E-1, 2, 3)
ICC Federated (H-1, 2)
SK Products by McCrometer (www.mccrometer.com) (H-1, 2)
Krohne America Inc. (www.krohneamerica.com) (H-1)
Omega Engineering Inc. (www.omega.com) (D, F, H-1, 2)
Orange Research (www.orangeresearch.com) (H-1)
SOR Inc. (www.sorinst.com) (B, D, H-1)
Universal Flow Monitors Inc. (www.flowmeter.com) (D, H-1)

I. Microwave
AM Sensors Inc. (I-3)
Monitor Technologies (www.monitortech.com) (I-3)

Magnetrol International (www.magnetrol.com) (I-3)
ThermoRamsey (www.thermoramsey.com) (I-3)

J. Surface charge
Auburn Systems LLC (www.auburnsystems.com) (J-3)

Flow switches are used to determine if the flow rate is above or below a certain value. This value (the setpoint) can be fixed or adjustable. When the setpoint is reached, the response can be the actuation of an electric or pneumatic circuit. When the flow switch is actuated, it will stay in that condition until the flow rate moves back from the setpoint by some amount. This difference between the *setpoint* and the *reactivation point* is called the switch *differential*. The differential can be fixed or adjustable. If the differential is small, the switch is likely to cycle its control circuit as the flow fluctuates around its setpoint.

In certain applications, a manual reset feature is desirable. This will guarantee that, once the switch is actuated, it will not be allowed to return to its preactuation state until manually reset by the operator. This feature is designed to require the operator to review and eliminate the cause of the abnormal flow condition before resetting the switch.

All instruments that can measure flow can also be used as flow switches. On the other hand, if only a flow switch is required for a particular application, the installation of indicating or transmitting devices cannot be economically justified. Therefore, in this section, only the direct flow switches will be discussed. Indirect devices, such as differential-pressure switches piped around orifice plates and receiving switches connected to the output signals of transmitters, are not covered.

DESIGN VARIATIONS

The least expensive and therefore the most widely used are the various paddle-type devices. At "no flow," the paddle hangs loosely in the pipe in which it is installed. As flow is initiated, the paddle begins to swing upward in the direction of the flow stream. This deflection of the paddle is translated into mechanical motion by one of several techniques, including a pivoting cam, a flexure type, or a bellows assembly. The mechanical motion causes the switch to open or close. If a mercury switch is used, the mechanical motion drives a magnetic sleeve into the field of a permanent magnet that trips the switch. A hermetically sealed switch will be directly actuated by the permanent magnet as it moves up or down according to the paddle movement. If a microswitch is used, the translated motion will cause direct switch actuation.

The range and actuation point of paddle switches can be changed and adjusted by changing the length of the paddle. For any given pipe size, the actuation flow rate decreases as the paddle length increases.

Paddle-type flow switches are sensitive to pipeline turbulence, pipeline vibration, and installation configuration. For these reasons, it is advisable to provide them with the equivalent of a 10-pipe-diameter straight upstream run, to use dampers if pipe vibration or pulsating flow is expected, and to readjust their settings if they are to be mounted in vertical upward flow lines. The conventional paddle-type designs are incapable of distinguishing low flow velocities from no-flow conditions. Therefore, if lower flows are to be detected, the folding circular paddle should be used (Figure 2.7a), which permits the full diameter paddle to fold back upon itself to minimize pressure drop.

In smaller pipelines where it is desired to provide local flow indication, the variable-area-type flow switches can be considered in addition to the flow switch action. If the vertical upward flow configuration of the rotameter design is not convenient from a piping layout point of view, the circular swinging vane design, illustrated in Figure 2.7b, can be considered. In existing systems, the clamp-on-type ultrasonic liquid flow switch can be a convenient solution, because it does not require process shutdown or pipe penetration. If the purpose of the flow switch is to protect pumps from running dry, the wafer-type capacitance insert unit is a good choice (Figure 2.7f).

Flow switch reliability is increased by the elimination of moving parts so that pipe vibrations or fluid flow pulses will

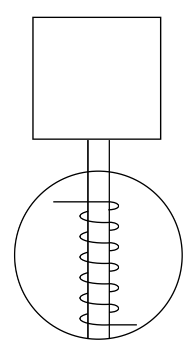


FIG. 2.7a
Folding paddle switch.

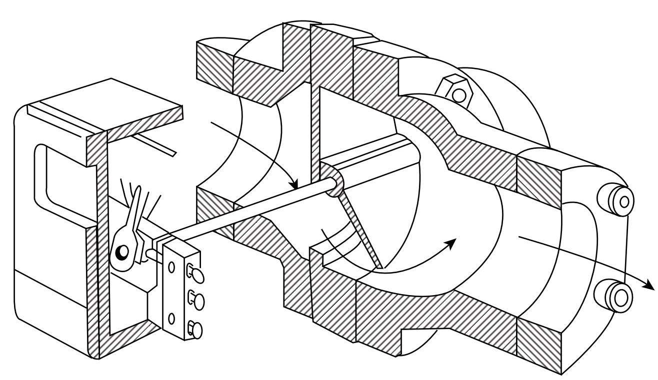


FIG. 2.7b
Swinging vane flow switch.

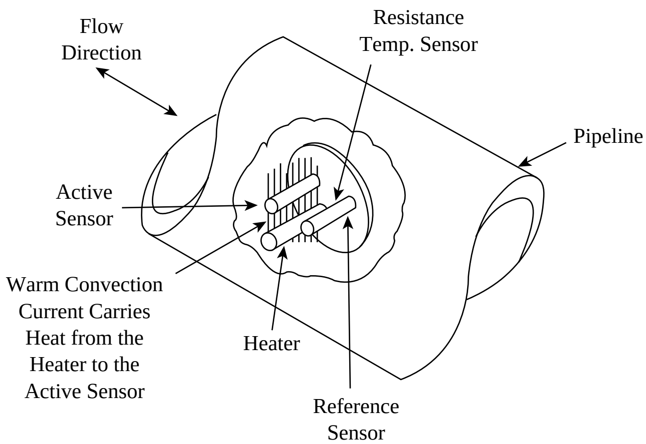


FIG. 2.7c
Thermal flow switch.

TABLE 2.7d
Minimum Settings for Flow Switches

	Minimum Velocity in ft/min (m/min)	
Flow Switch Type	*Air*	*Water*
Thermal	10 (3)	0.5 (0.15)
Variable Area	300 (91)	20 (6)
Ultrasonic	—	60 (18)
Paddle	300 (91)	60 (18)

not cause erroneous switch actuation. One of the most popular solid-state designs is the thermal flow switch. All heat-actuated flow switches sense the movement or stoppage of the process stream by detecting the cooling effect (temperature change) on one or more probes. They are available both in the flow-through and in the probe configuration. One design consists of a heater probe and two sensor probes connected in a Wheatstone bridge. When the flow stops, an imbalance in the bridge circuit occurs, as illustrated in Figure 2.7c. The main advantage of this design is its ability to detect very low flow velocities (Table 2.7d). Its main limitation is that it cannot respond instantaneously to flow changes. Depending on switch adjustments and on type of process fluid, the speed of response will vary from 2 sec to 2 min.

The valve body-type flow switches are built into a pipe fitting that resembles the body of a single seated globe valve. A flow disk is allowed to move in a vertical direction within what is normally considered the valve seat. A magnetic sleeve is mounted above the flow disk and, as the disk is lifted upward due to initiation of flow, a mercury switch is actuated by the movement of the magnetic sleeve into the field of the externally mounted permanent magnet.

A bypass-type switch (Figure 2.7e) has an externally adjustable vane that creates a differential pressure in the flow stream. This differential pressure forces a proportional flow through the tubing that bypasses the vane. A piston retained by a spring is in the bypass tubing and will move laterally

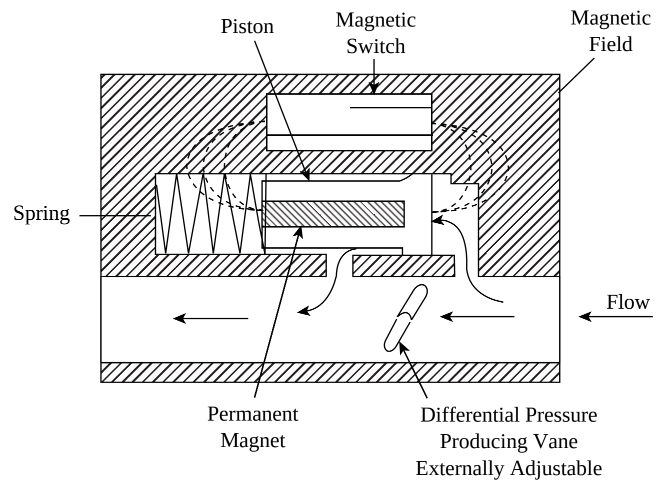


FIG. 2.7e
Bypass flow switch.

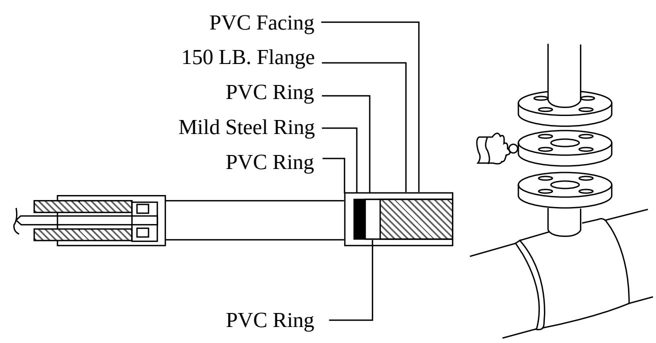


FIG. 2.7f
Capacitance-type flow/no-flow switch. (Courtesy of Endress + Hauser Inc.)

as flow increases or decreases; the piston's movement actuates a switch. Bypass flow switches can be used for fairly low flow rates, and their ability to be externally adjusted is a very desirable feature.

Capacitance-type ring sensors can detect the absence or presence of liquids or slurries, which usually relates to flow/no-flow conditions. This can prevent pumps from running dry or cavitating. The ring sensor (Figure 2.7f) is a capacitance switch that fits between two flat-faced flanges in standard pipe sizes between 2 and 8 in. (50 and 200 mm). When the ring sensor contains air (no-flow condition), it detects a dielectric constant of 1. When flow starts, it detects the dielectric constant of the flowing fluid, which is greater than 1, which causes a corresponding increase in radio frequency (in the megahertz range) current flow. The circuitry detects this current flow and operates the switch accordingly. An adjustable time delay of 0 to 20 sec is provided to protect from premature shutdowns. The construction materials are usually PVC and steel, with the electronics housed in explosion-proof or water-tight aluminum or thermoplastic housing. The operating temperature range for the standard ring sensor is 0 to 212°F (–18 to 100°C).

SOLIDS FLOW SWITCHES

In pneumatically conveyed or gravity-flow-type solids handling systems, it is important to quickly detect blockages or other abnormal conditions, such as feed loss, bin bridging, cyclone overflow, or the rupture of baghouse filters. The flows of certain powders (such as flyash, cement, or alumina) are particularly difficult to detect. Level sensors; tilt switches; and capacitance, radiation, sonic, and optical devices have been used in the past to detect abnormal flow conditions. In addition to these, one can also measure the flow rate of these solids' flows by the following techniques.

One solids flow switch, the "Triboflow," collects, on its probe surface, the static charges of the solid particles passing over its surface. The resulting current is related to the flow rate of solids. These probes are sensitive enough to detect flow increases as small as what results from baghouse rupture. These probe-type solids flow switches are inexpensive and can be installed in hazardous areas.

Microwave switches detect the flow of solids by detecting motion or the absence of it. In the microwave-type motion detector, the transducer emits a 24-GHz signal into the flowing solid stream and analyzes the reflected frequency (Doppler effect) to determine the speed of the object that reflected it. The sensitivity of the solids flow switch is adjustable, so it might be used to detect flow/no-flow or trip at a velocity as low as 6 in./min (15 cm/min) when the pipe is full or at a velocity of one particle every 5 sec in a free-falling gravity flow system. Units are available in aluminum or stainless steel. They can be connected to a pipe by a coupling or flange (see Figures 2.7g and 2.23w), or they can view through windows or nonmetallic walls without any openings. The units are intrinsically safe and can be used at working pressures up to 15 PSIG (1 bar). The switch can also observe motion at a distance of several feet from the detector and can tolerate 0.5 in of nonconductive coating buildup or 0.1 in of conductive coating buildup.

FIG. 2.7g
Microwave solids flow switch, flanged. (Courtesy of ThermoRamsey Inc.)

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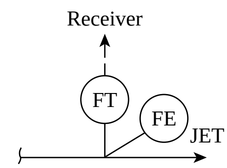
2.8 Jet Deflection Flow Detectors

D. S. KAYSER (1982) **B. G. LIPTÁK** (1995, 2003)



Flow Sheet Symbol

Maximum Process Pressure	10 PSIG (0.7 bar)
Design Temperature	450°F (232°C) standard and up to 1200°F (650°C) special
Standard Materials	Type 316 stainless steel
Connection and Insertion	Standard connection is 3 in. flanged; insertion depth is adjustable from 0 to 60 in. (0 to 1.5 m).
Air (Nitrogen) Requirement Pressure	10 to 90 PSIG (0.7 to 6.2 bar) over process pressure
Flow	2.5 and 5.0 SCFM (71 to 142 l/min)
Velocity Ranges	0 to 50 ft/sec and 0 to 85 ft/sec (0 to 15 m/sec and 0 to 26 m/sec)
Output Differential Range	0 to 80 in H_2O and 0 to 130 in H_2O (0 to 20 kPa and 0 to 32 kPa)
Inaccuracy	±2% of full scale (if sensor is inserted to average velocity point in the duct)
Rangeability	20:1
Cost	About $2500 to $5000; varies with accessories
Partial List of Suppliers	Fluidynamic Devices Ltd. United Scientific/Monitor Labs (formerly Lear Siegler Measurement Controls Corporation)

OPERATING PRINCIPLE

Volumetric flow rate in a pipe or duct can be inferred from a measurement of gas velocity, and one of the methods to measure this velocity is jet deflection detection. The operation of this sensor requires the blowing of air (or some other gas that is compatible with the process) through a nozzle, which forms a jet as shown in Figure 2.8a. The jet is centered between the two receiver ports when there is no flow in the process pipe or duct. In that case, the differential pressure between the two ports is zero. As a process flow is initiated, the jet is deflected, and the amount of this deflection will be related to the velocity of the flowing process stream. Figure 2.8a shows how the pressure profile of the jet shifts as the velocity of the process stream increases.

The deflection of the jet will cause an increase in the pressure at the downstream port and a decrease at the upstream port. The geometry of the ports is so designed that, over the useful

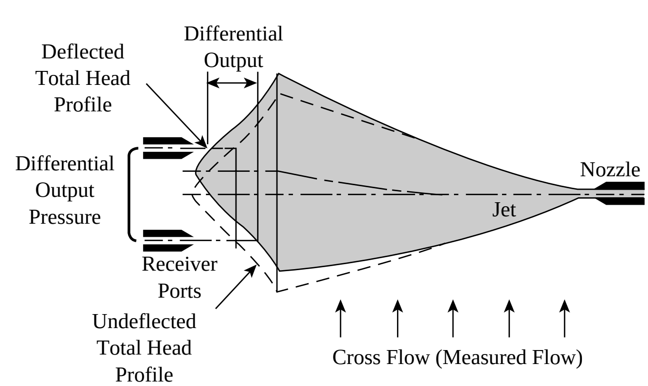


FIG. 2.8a
Pressure profile generated by a jet deflection-type flow detector.

range of the element, the change in differential pressure is linearly proportional to the velocity of the process stream. The actual value of this pressure differential is a function of the product of the process velocity and the square root of the gas density. If the density is constant, the pressure drop varies linearly with gas velocity. If the particulate concentration in the process fluid (flue or stack gases) is separately measured, this reading will yield the mass emission rate of particulate materials.

In some respects, this flowmeter is similar to the conventional pitot tube. Similarities include the negligible pressure drop created, the high speed of response, and the retractable design, which can be used for wet tapping or to measure flow profiles by traversing the cross section of the pipe or duct. On the other hand, the jet-deflection sensor has features that are superior to those of conventional pitot sensors.

These advantages include the existence of a continuous back-purge and of the auxiliary cleaning jets, which keep the receiver ports clean. Another advantage is that the element is heated to a temperature above the dew point, so condensation is avoided. In addition, the output signal is not only linear but is also much stronger than that of a conventional pitot element. At a supply pressure of 50 PSIG (345 kPa), the output differential-pressure signal generated about 1.5 in of water column per each ft/sec (0.3 m/sec), which is about 100 times what is generated by a pitot tube.

The relationship between process gas velocity and flow rate is

$$Q = 60VA \qquad \textbf{2.8(1)}$$

where

Q = flow rate, in actual cubic feet per minute (ACFM)
V = velocity, feet per second (ft/sec)
A = pipe or duct cross-sectional area, square feet (ft^2)

In case of laminar flow in a circular duct, the profile is parabolic with the maximum velocity at the center and zero velocity at the walls. In this case, the maximum velocity is twice the average; therefore, the reading taken at the center of the duct will be twice the average for the laminar flow case. In turbulent flow in a circular duct, the average velocity point is located at approximately 25% of the radius as measured from the duct wall. The accurate determination of average velocity in rectangular ducts is more complicated, and no simple rules of thumb can be given. The point velocity, in general, is inaccurate, because the velocity profile is not uniform.

In many actual installations, the point of average velocity will not be located at the predicted insertion depth because of disturbances introduced by the upstream piping configuration. For proper operation, the upstream piping should be straight for at least 20 pipe diameters to allow for the disturbances to smooth out. When this upstream straight run requirement cannot be met, an average velocity point can sometimes be found by traversing the duct and making a number of measurements at a number of points across the cross section.

A traverse should always be made on rectangular ducts, if accurate measurement is required. Traversing rectangular ducts is time consuming because of the need for traversing in two or more planes. In addition, the average velocity points can shift as flow rates vary in both the rectangular or circular ducts.

HOT-TAPPING

Probe-type instruments, such as the jet deflection type element or the pilot tube, can be installed so that they can be removed for inspection without shutting down the process. Figure 2.8b shows the detail of such a *hot-tapping* installation, which makes it possible to remove the probe while the pipe is under pressure. To remove the sensor, first the gland nut is loosened sufficiently to allow the withdrawal of the shaft of the element until it is outside of the gate valve and in the "outside chamber." The valve is then closed, the outside chamber is vented, and the gland nut is removed to allow the safe removal of the element.

Normally, the jet deflection element is installed in piping that is under low pressure or vacuum; thus, the risk of having the element blow out during removal is slight. Nonetheless, it is recommended to install stop rods or safely chains so as to completely eliminate the possibility of injury caused by a blowout.

The step-by-step hot-tapping procedure is shown in Figure 2.8c. The first step is to weld a flanged nozzle to the pipe that is to be tapped. As the second step, a flanged gate valve is attached to the weld neck flange. The third step is to bolt a hot-tapping drill to the downstream side of the gate valve. After the gate valve is opened, the hot-tapping machine drills through the wall of the process pipe. Rigid safety procedures must be enforced during hot-tapping operations, particularly if the process is flammable or hazardous. Hot-tapping can be performed only if the piping specification does

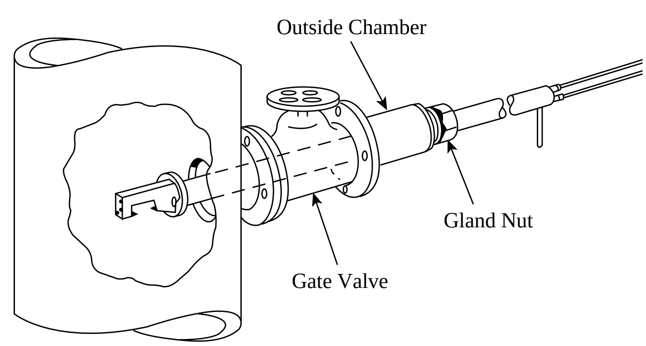


FIG. 2.8b
Hot-tap installation allows for the removal of the flow element, while the pipe or duct is under pressure.

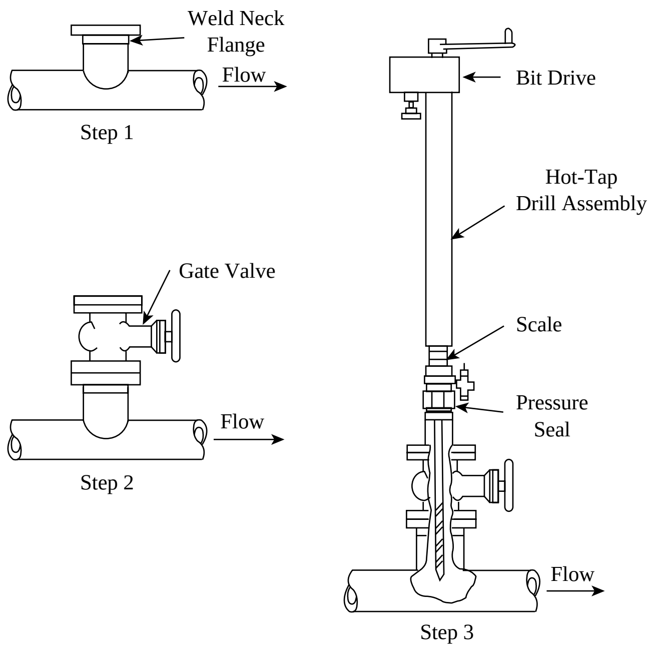


FIG. 2.8c
Hot-tapping procedure.

not require that welds be stress relieved and if there is flow in the pipe so that the heat of welding and drilling is removed.

The pressure seal on a hot-tap machine is similar in its design to that of a control valve packing box and it allows the tapping of pipes under relatively high pressures. A hand-operated drilling assembly is shown in the figure, but units are also available with pneumatic or electric drives. A scale is provided on the machine, showing the depth to which the operator has drilled into the pipe. After the drilling is done, the bit is retracted, the valve is closed, and the hot-tap machine is removed. The tap is now ready to accept the gland nut and outside chamber, which is provided with the flow element as shown in Figure 2.8b.

CONCLUSION

Jet deflection flow detectors can be considered for flow measurement in low-pressure, circular, or rectangular ducts. They can be periodically purged or flushed and can be removed for inspection and cleaning. They are suitable for dirty, abrasive, corrosive, and plugging services. Their accuracy of ±2% of full scale is usually acceptable for making flow measurements around flare headers, stacks, and air ducts. It should be remembered that the actual installed accuracy is dependent on one's ability to insert the element to a depth at which the velocity is the average of the velocity profile across the duct.

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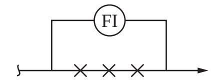
2.9 Laminar Flowmeters



Flow Sheet Symbol

R. SIEV (1969) **B. G. LIPTÁK** (1995) **J. B. ARANT** (1982, 2003)

Design Pressure	Up to 5000 PSIG (34 MPa)
Design Temperature	Up to 300°F (150°C) normally, but can be higher with special designs
Material of Construction	Stainless steel, aluminum, or any alloy available in small bore tubing
Fluids	Liquids and gases
Flow Range	0.0001 to 2000 scfm for gases (3 cm^3/min to 57 m^3/min) 0.0003 to 10 GPM for liquids (1 cm^3/min to 38 l/min)
Inaccuracy	0.5% to 1% of actual flow for commercial gas flow elements, if calibrated
Flow Turndown	10:1 minimum
Flow Characteristic	Linear to approximately linear
Costs	A 1/2-in. (13 mm) stainless-steel laminar flow element costs $700, a 2-in. (50 mm) unit costs $1500, and a 16-in. (300 mm) all-stainless unit costs $11,000. The differential-pressure readout devices are additional to the above element costs.
Partial List of Suppliers	Aalborg Instruments & Controls (www.aalborg.com) Alicat Scientific, ATC (www.alicatscientific.com) Chell Instruments Ltd. (UK), Hastings (www.chell.co.uk) CME, A Division of Aerospace Control Products (www.cmeflow.com) Matheson Tri-Gas (www.matheson-trigas.com) Meriam Instrument Division of Scott Fetzer (www.meriam.com) National Instruments (www.ni.com) Universal Flow Monitors Inc. (www.flowmeter.com)

Laminar flowmeters fill a special need in flow measurement where the requirements might include low to extremely low flow rates, linear calibration and low noise, the ability to measure high-viscosity liquids, or steady low-flow repeatability and control accuracy. Laminar flowmeters are intended for very low flow rates where other types of meters are either marginal in performance or cannot be used at all. Laminar flowmeters can be constructed by various methods, but the most common is with capillary tubes. Hence, the terms *laminar flowmeter* and *capillary flowmeter* are virtually synonymous. Proprietary commercial units use other matrix shapes and are intended for use with gases (Figure 2.9a). Where gas is metered, it is preferable to use calibrated commercial units instead of undertaking the design of a laminar flowmeter.

The flowmeter consists of the laminar flow element and a differential-pressure measuring instrument. While the flow is theoretically linear with pressure drop, in practice, some nonlinearities are often encountered. In most cases, these are of little consequence.

The theory for laminar flowmeters is based on the Hagen–Poiseuille Law for laminar flow and the Reynolds number as a means of defining the type of flow. Both are required to investigate and design a laminar flow element. More detailed explanations and discussions of theory can be found in any standard textbook on fluid mechanics.

THEORY

Fluid flow in pipes and tubes is characterized by a nondimensional number called the Reynolds number (Re). Up to approximately Re 2000, the flow is called laminar, viscous, or streamline. Above 10,000, the flow is called fully developed

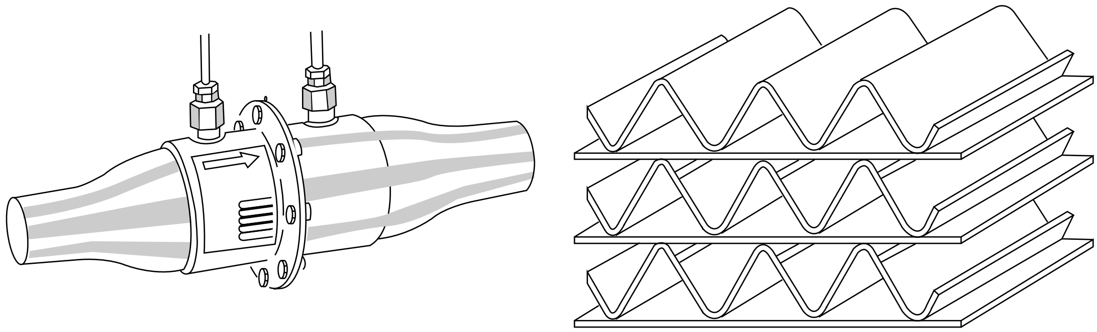


FIG. 2.9a
The laminar flowmeter and its matrix element with miniature triangular duct passage with under 0.1-mm effective diameters. (Courtesy of Meriam Instrument Div. of Scott Fetzer Co.)

turbulent. The region between 2000 and 10,000, where the flow is shifting from laminar to turbulent, is not clearly defined but is called transitional. Generally, laminar flow elements are restricted to numbers under 2000 and, most commonly, well below 1200. Certain methods will enable a capillary element to be used satisfactorily up to Re 15,000 with a modest sacrifice in error and linearity.

Reynolds number is defined by the following equations:

For liquid flow,

$$\mathrm{Re} = \frac{50.7\rho Q}{D\mu} \quad \text{or} \quad \mathrm{Re} = \frac{6.32W}{D\mu} \qquad \mathbf{2.9(1)}$$

where
Re = Reynolds number
ρ = density (lb/ft^3) at flowing temperature
Q = flow rate (gal/min)
D = internal tube diameter (in.)
μ = viscosity of flowing temperature (centipoise)
W = flow rate (lb/h)

For gas flow,

$$\mathrm{Re} = \frac{6.32\rho Q}{D\mu} \quad \text{or} \quad \mathrm{Re} = \frac{6.32W}{D\mu} \qquad \mathbf{2.9(2)}$$

where
ρ = density at standard conditions (lb/ft^3)
Q = flow rate (scfh)
Other units = as defined for liquid

For the laminar flowmeter shown in Figure 2.9a, the Reynolds number is limited to a range of 150 to 300 and is calculated as

$$\mathrm{Re} = 228(SG)(P)(\Delta P)/m\mu \qquad \mathbf{2.9(3)}$$

TABLE 2.9b
Gas Properties under the Standard Conditions of 29.92 in of Mercury and 70°F (760 mm of Mercury and 21°C)

Gas	*Density (lb/ft^3)*	*μ Viscosity, Micropoise*	*Specific Gravity*
Air	0.0749	181.87	1.000
Argon	0.1034	225.95	1.380
Helium	0.0103	193.9	0.138
Hydrogen	0.0052	88.41	0.0695
Nitrogen	0.0725	175.85	0.968
Oxygen	0.0828	203.47	1.105
Carbon dioxide	0.1143	146.87	1.526

where
SG = specific gravity relative to air (Table 2.9b)
P = flowing gas pressure in inches of mercury absolute
ΔP = differential pressure in inches of water
$m\mu$ = viscosity of the flowing gas in micropoise (Table 2.9b)

Hagen–Poiseuille Law

Once the tube inside diameter required to give laminar flow according to the Reynolds number calculation has been defined, the length of the capillary has to be determined to design the laminar flowmeter system. These equations are as follows.

For liquid flow,

$$L = 1.5876 \times 10^3 \frac{\Delta P D^4}{\mu Q} \qquad \mathbf{2.9(4)}$$

or

$$L = \frac{\Delta P D^4 \rho}{7.86 \times 10^5 \mu W} \qquad \mathbf{2.9(5)}$$

where

L = length of tube (in.)
ΔP = differential pressure drop (in water)
D = tube internal diameter (in.)
μ = viscosity at flowing temperature (centipoise)
ρ = density at flowing temperature (lbm/ft^3)
Q = flow rate (gal/min)
W = flow rate (lbm/h)

Equation 2.9(5) can also be used for calculating a gas flow capillary element if the value of ΔP is no greater than 10% of the inlet pressure. Otherwise, changes in gas density, specific volume, and flow velocity cause too many complications in the calculations. While the calculation is in weight units, this can be easily converted to any desired scale units.

Design Parameters

There are a number of guidelines for successful design of a laminar flowmeter.

1. The differential pressure drop can range from 5 to 800 in. of water (1.24 to 200 kPa).
2. $(L/D)/\text{Re}$ should be a minimum of 0.3; for best linearity, a value of 0.6 or greater is preferable. Large L/D ratios and/or lower Reynolds numbers contribute to accuracy. For example, the entrance effect for laminar flow is negligible if $(L/D)/\text{Re} > 0.3$ and $\text{Re} < 500$.
3. The area of the flow conduit preceding the capillary should be a minimum of 20 times the capillary area.
4. The differential-pressure instrument's pressure connections should be located 100 to 200 capillary diameters from the capillary ends.
5. A filter capable of removing particles 0.1 in. (2.54 mm) or larger than the capillary internal radius should be installed upstream of the system.
6. The metering system should be sloped up for liquids to permit gas venting and sloped down for gases to permit liquid draining.
7. Examination of the Hagen-Poiseuille equation shows that viscosity is a primary variable; changes in viscosity can result in large flow measurement errors. With a known fluid or composition, the only thing that affects viscosity is temperature. For this reason, the temperature must be known and held essentially constant. This can be done by immersing the metering system and measuring capillary in a constant temperature bath as shown in Figure 2.9c. If the flow is measured in weight units such as pounds per hour, then fluid density must be known. Fluid density also varies with temperature, but controlling the temperature to fix viscosity will also fix density. With some fluids, cooling may be required instead of heating, but the overall principle is the same.

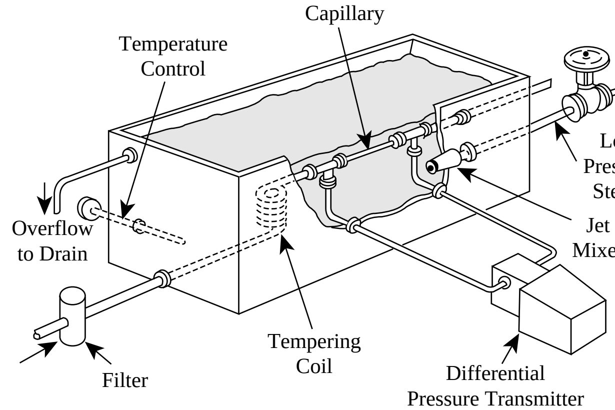


FIG. 2.9c
Typical capillary with constant temperature bath.

Design Calculations for Liquid Service

Based on the flow rate and the viscosity of the fluid, select a tube internal diameter that will result in a Reynolds number within the laminar range and preferably less than 1200. Calculate the length of tubing required using the selected tube diameter to ensure that it is a reasonable length and that it meets the $(L/D)/\text{Re}$ criteria. By working back and forth between the various equations, the system can be tailored to meet almost any design criteria. For example, let us assume that it is desired to design a capillary flowmeter to measure a small liquid catalyst stream, and the basic data for the catalyst flow is as follows:

Maximum flow capacity: 50 lbm/h
Viscosity: 20 cP at 100°F
Density: 53.8 lbm/ft^3
Desired instrument ΔP: 100 in of water

Small-diameter, standard stainless-steel tubing is readily available and should be used. To design as linear and accurate a flowmeter as possible, a tube bore that provides a large $(L/D)/\text{Re}$ is desirable. To minimize plugging problems and to enable the use of a filter that won't clog easily, start by looking at a 3/16 × 0.032-in. wall thickness tubing with a nominal internal diameter of 0.1235 in. From Equation 2.9(1),

$$\text{Re} = \frac{6.32W}{D\mu} = \frac{6.32 \times 50}{0.1235 \times 20} = 128 \qquad \textbf{2.9(6)}$$

This is well into the laminar range, so the length of the flow element can be calculated to determine if it will make a reasonable design. From Equation 2.9(5),

$$L = \frac{\Delta P D^4 \rho}{7.86 \times 10^{-5} \mu W} = \frac{100 \times 0.1235^4 \times 53.8}{7.86 \times 10^{-5} \times 20 \times 50} = 15.7\,\text{in.} \qquad \textbf{2.9(7)}$$

$$(L/D)\,\text{Re} = (15.7/0.1235)/128 = 0.993 \qquad \textbf{2.9(8)}$$

This is an easy length to work with in fabricating a meter element and a constant temperature bath, and it looks like a reasonable design based on the criteria.

ERROR SOURCES

Changes in viscosity and density can result in flow measurement errors. Viscosity changes in liquid as a result of temperature can be substantial, while density changes are more moderate. With gases, the reverse is usually true, with temperature having more influence on density and less on viscosity. The need for careful control of the operating temperature to minimize these effects must be emphasized.

From Equations 2.9(4) and 2.9(5), it can be seen that internal diameter of the tube is very important, because it is multiplied to the fourth power. While high-quality tubing will be very close to published specifications, manufacturing tolerances will result in variations from these dimensions, both laterally and longitudinally. If the actual effective internal diameter of the capillary tube differs by 1% from the value used in the calculation for a given ΔP, an error of about 4% will result. Therefore, the laminar flowmeter should be calibrated on a known fluid before use, and appropriate design adjustments should be made as necessary.

To measure the true capillary differential pressure drop according to the Poiseuille equation, it would be necessary to put the pressure taps into the capillary at the calculated L dimension. This is impractical because of the small tubing. A pressure tap must be perfectly flush with the inside of the tube and must be clean with no burrs or other projections into the tube. Otherwise, considerable differential-pressure measurement error will result. Using practical methods of constructing a capillary flowmeter, there are three additional sources of pressure drop in addition to the capillary loss. These are all additive and will give a greater indicated pressure drop than the capillary flow alone. These three sources of error are inlet loss, exit loss, and capillary entrance loss. These losses also contribute to nonlinearity.

There is very little loss from the entrance fitting into the capillary tube if laminar flow conditions exist. But if the piping cavity ahead of the capillary is extremely large relative to the capillary (approximating a reservoir) and the fluid velocity is thus extremely low (approaching zero), there can be an inlet effect and pressure loss.[1] This is a result of the sudden contraction from the large reservoir to the small tube bore, forming a bell-mouth shape approach flow. This loss can be expressed as

$$\Delta P_i = \frac{2.8 \times 10^{-7} W^2}{D^4 \rho} \qquad \textbf{2.9(9)}$$

This equation is derived from Bernoulli's equation for flow out of a reservoir.

When the fluid exits the capillary, the flow path enlarges. If the piping is similar to that described under inlet loss, the loss can be calculated by

$$\Delta P_e = \frac{5.6 \times 10^{-7} W^2}{D^4 \rho} \qquad \textbf{2.9(10)}$$

Entrance loss occurs in addition to the normal capillary pressure drop in the initial fluid path distance or, to state it in another way, for a short distance the pressure drop is higher than that predicted by the Poiseuille Equation.[2,3] The additional loss is due to the work expended in the formation of the parabolic velocity distribution profile characteristic of laminar flow. It can be expressed in terms of an equivalent length of capillary, L_{eq}, added to that calculated by the Poiseuille equation. Refer to Figure 2.9d for determining the L_{eq}.

The following equation can be used for the pressure drop:

$$\Delta P_{en} = \frac{1.96 \times 10^{-7} W^2}{D^4 \rho} \qquad \textbf{2.9(11)}$$

Table 2.9e can be used as a quick guide for judging the design factors that will minimize overall entrance effects. For the conditions given in the table, the error involved will be less than 1%. In general, the effect of all of the above errors will be minimized if the Reynolds number is low, the laminar flow element is long, and the pressure drop is high. The overall

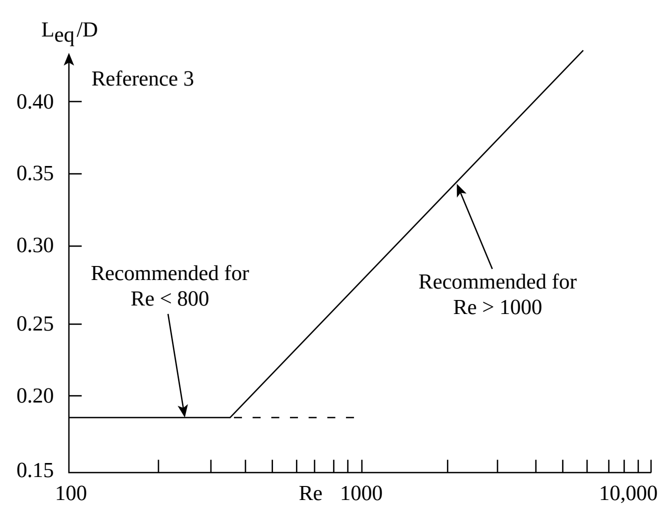


FIG. 2.9d
Equivalent length of capillary (L_{eq}).

TABLE 2.9e
L/D Ratio to Minimize Entrance Effect

Re	10	50	100	500	1000	2000
L/D>	15	75	150	750	1500	3000

error can be calculated by this equation as

$$\text{Percent error} = \frac{\Delta P_i + \Delta P_e + \Delta P_{en} \times 100}{\Delta P} = \frac{0.367W \times 100}{\mu L} \quad \mathbf{2.9(12)}$$

RANGE EXTENSION TECHNIQUES

Two techniques are used to expand the range capability of laminar flow elements. One is to use a number of capillary tubes in parallel. The other is to use a tight helical coil capillary. The choice of technique depends on such factors as desired flow rate, nonlinearity requirements, Reynolds number, capillary length, and system space design limitations.

If the amount of flow desired is greater than can be conveniently handled by a single capillary, the flow can be split into many smaller units as necessary.[4] Units with matrix elements (Figure 2.9a) or with more than 900 individual capillary tubes have been built and used successfully. The mechanical construction of multiparallel capillaries can be a problem. Tube packing voids may not affect meter operation but add considerable difficulty to calculating the meter range. Normally, it is best to eliminate the voids by filling the spaces with solder, braze material, or plastic resin; the filler material chosen will depend on fluid compatibility and operating conditions. Overall, it is a tricky mechanical design.

Coiling a length of straight capillary results in a flow phenomenon called the *Dean effect*. When a fluid flows through a curved pipe or coil, a secondary circulation of fluid, known as a double eddy, takes place at right angles to the main direction of flow. This circulation accounts for the fact that the pressure drop in curved pipe is greater than in a corresponding length of straight pipe. The Dean effect stabilizes laminar flow and raises the Reynolds number at which turbulent flow starts. It has been established that this will allow properly designed coiled capillaries to be operated up to a Reynolds number of 15,000.[5] The Reynolds number at which laminar flow can be sustained for various coil curvature ratios is called the *critical Reynolds number*. It is a function of the internal diameter of the tube and the coil tightness or diameter. Table 2.9f gives the approximate critical Reynolds number at which laminar flow can be sustained for various coil curvature ratios.

In this table, D is the tube inside diameter, and Dc is the mean coil diameter, centerline to centerline. From a practical viewpoint, the ratio of $D/Dc = 1/9$ is equivalent to the maximum allowable critical Reynolds number of 15,000 and can be used as a safe design in most cases.

The pressure drop of laminar flow through coils can be expressed in terms of an equivalent length, L_e, of straight pipe of the same diameter and shape which will have the same friction loss as the curved pipe. The ratio of the equivalent to actual coil length, L_e/L is a function of the Dean number, or $\text{Re}(D_C/D)^{1/2}$, as shown in Figure 2.9g. This curve is accurate to about ±5%.

TABLE 2.9f
Critical Reynolds Number vs. Coil Curvature Ratio

Coil Curvature Ratio (Dc/D)	Critical Reynolds Number $(Re)_c$
Straight Pipe	2100
2000	2700
1000	2900
500	3200
100	4600
50	5700
10	10,000
9	15,000

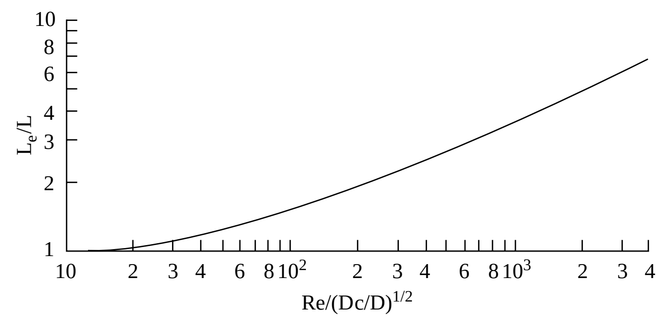


FIG. 2.9g
Equivalent lengths for curved pipe.

The equation for calculating the length of a coiled capillary required to meet a specific metering design is expressed by

$$L = \frac{\Delta P D^4 \rho}{7.86 \times 10^{-5} \mu W C} \quad \mathbf{2.9(13)}$$

where C = the coil factor correction.

The coil factor correction is a function of the term $\text{Re}(D/D_C)^{1/2}$. Refer to Figure 2.9h for C vs. $\text{Re}(D/D_C)^{1/2}$ or to Figure 2.9i for C versus Re for various D/Dc ratios. In very small capillaries, the coil diameter can be the nominal value, since exact centerline measurement is insignificant.

In laminar flow, the friction factor is a function of Reynolds number only and is independent of surface roughness.

The friction factor can be expressed as

$$f = 16/\text{Re} \quad \mathbf{2.9(14)}$$

Therefore, the Fanning equation 2.8(15) can be used as an alternate means of calculating the capillary element as shown by

$$L = \frac{2\Delta P g_c D}{4 f \rho V^2} \quad \mathbf{2.9(15)}$$

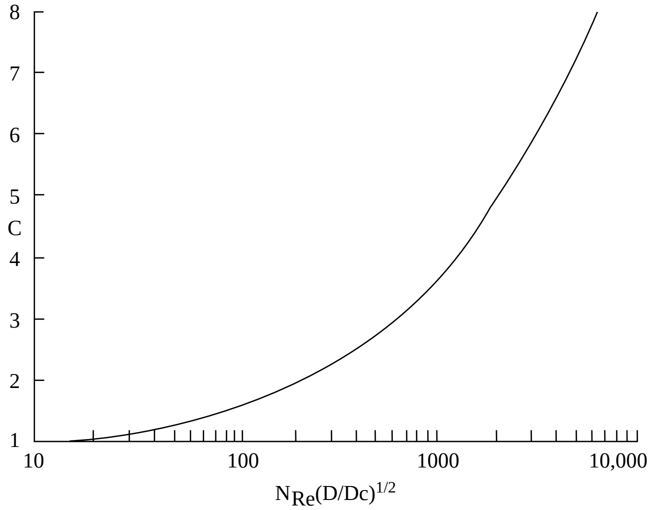


FIG. 2.9h
Correction factors for coiled capillary flowmeter (data adapted from reference 5).

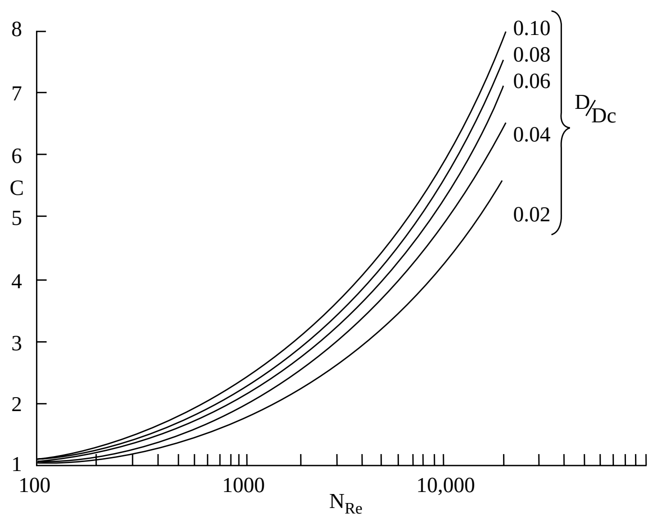


FIG. 2.9i
Correction factors for coiled capillary flowmeters (data adapted from reference 5).

where

L = capillary length (ft)
ΔP = pressure drop (lbf/ft^2)
g_c = gravity constant 32.17 (ft/sec^2)
D = capillary internal diameter (ft)
ρ = fluid density (lbm/ft)
V = fluid velocity (ft/sec)

COMMERCIALLY AVAILABLE UNITS

In the past decade, the use of laminar flowmeters has greatly expanded, and the number of suppliers has also increased. Their applications range from the testing of internal combustion equipment to semi-conductor manufacturing, leak testing, and fan or blower calibration. Standard units are available in several materials, including stainless steel. They can be provided with a variety of connections and in sizes ranging from 0.25 to 16 in. (6 to 400 mm).

In terms of airflow capability, these units range from 5 cc/min to approximately 65 cubic meters/min (2285 SCFM). Pressure differentials generated by the laminar flow elements are usually under 20 in. of water (510 mm of water). The recommended installation practice is to provide 10 to 15 diameters of straight pipe upstream of the flow element. Installation of a filter is also recommended at the meter inlet. In engine testing, a backfire trap is also desirable to prevent carbon deposits on the matrix element.

The measurement error is usually between 0.5 and 1% of actual flow within a 10:1 range. However, this performance is a function of both the quality of calibration of the system and of the precision of the d/p detector.

CONCLUSION

Laminar flowmeters are highly useful in measuring low flow rates of liquids and gases. Design of the elements is based on the use of the Reynolds number and Poiseuille's law. Design for most units is relatively simple, but fabrication of a complete unit and system can be complex. Simple capillary units can be fabricated by the user, but most require manufacturers' skills and design knowledge.

It is highly recommended that the final system be calibrated with the same type of fluid as the fluid upon which the sensor will operate, such as air or nitrogen for gas services and water for liquid services. After such calibration, the conversion is easily made to the actual fluid. The critical consideration is to calibrate the unit under conditions that will approximate the actual in-service Reynolds number of the application. Some sources of calibration services, other than the manufacturers, are the National Institute of Standards and Technology (NIST), Edison ESI, and the Colorado Engineering Experiment Station, Inc. (CEESI).

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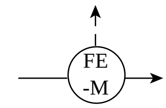
2.10 Magnetic Flowmeters

J. G. KOPP (1969, 1982) **B. G. LIPTÁK** (1995) **H. EREN** (2003)



Magnetic
Flow Sheet Symbol

Design Pressure	Varies with pipe size; for a 4-in. (100-mm) unit, the maximum is 285 PSIG (20 bars); special units are available with pressure ratings up to 2500 PSIG (172 bars)
Design Temperature	Up to 250°F (120°C) with Teflon® liners and up to 360°F (180°C) with ceramic liners
Materials of Construction	Liners: ceramics, fiberglass, neoprene, polyurethane, rubber, Teflon, vitreous enamel Kynar Electrodes: platinum, Alloy 20®, Hasselloy C, stainless steel, tantalum, titanium, tungsten carbide, Monel®, nickel, platinum-alumina ceramic
Type of Flow Detected	Volumetric flow of conductive liquids, including slurries and corrosive or abrasive materials
Minimum Conductivity Required	The majority of designs require 1 to 5 µS/cm. Some probe types require more. Special designs can operate at 0.05 or 0.1 µS/cm.
Flow Ranges	From 0.01 to 100,000 GPM (0.04 to 378.000 l/min)
Size Ranges	From 0.1 to 96 in. (2.5 mm to 2.4 m) in diameter
Velocity Ranges	0–0.3 to 0–30 ft/sec (0–0.1 to 0–10 m/sec)
Power Consumption	20 W with DC excitation, 30 W for a 2-in. (50-mm) AC and 0.3 kW for a 30-in. (760-mm) AC unit.
Input Signals	Voltage signal from detector proportional to flow rate; digital input 20 to 30 VDC for range switching, totalizer control, zero adjustment
Output Signal	4 to 20 mA DC, digital outputs for pulse outputs, multirange selection, high and low limits, empty pipe alarm, preset count, and converter failure outputs
Communication Output	Digital signal is superimposed on 4- to 20-mA; current signal conforms with HART protocol
LCD Display	Two-line, line, or dot matrix
Surge Protection	Arresters are installed in the power supply and current signal output circuits
Error (Inaccuracy)	±1% of actual flow with pulsed DC units within a range of up to 10:1 if flow velocity exceeds 0.5 ft/sec (0.15 m/sec); ±1% to ±2% full scale with AC excitation
Cost	The least expensive designs are the probe versions that cost about $1500. A 1-in. (25-mm) ceramic tube unit can be obtained for under $2000. A 1-in. (25-mm) metallic wafer unit can be obtained for under $3000. An 8-in. (200-mm) flanged meter that has a Teflon liner and stainless electrodes and is provided with 4- to 20-mA DC output, grounding ring, and calibrator will cost about $8000. The scanning magmeter probe used in open-channel flow scanning costs about $10,000.
Partial List of Suppliers	ABB (www.abb.com) AccuDyne Systems Inc.

Advanced Flow Technology Co
Arkon Flow Systems (www.arkon.co.uk)
Badger Meter Inc. (www.badgermeter.com)
Baily Controls Co.
Bopp & Reuther Heinrichs Messtechnik (www.burhm.de)
Brink HMT
Brooks Instrument Div. of Emerson (www.emersonprocess.com)
Burkert GmbH & Co. KG
Cole-Parmer Instrument Co. (www.coleparmer.com) (probe)
Colorado Engineering Experimental Station
Control Warehouse
Danfoss A/S (www.danfoss.com)
Dantec Electronics
Datam Flutec
Davis Instruments
Diesel GmbH & Co.
H.R. Dulin Co.
Dynasonics Inc. (probe-type)
Electromagnetic Controls Corp.
Elis Plzen
Endress+Hauser Inc. (www.usendress.com)
Engineering Measurements Co.
EMCO (www.emcoflow.com)
Euromag (www.euromag.net)
Fischer & Porter Co.
The Foxboro Co. (www.foxboro.com)
Honeywell Industrial Control (www.honeywell.com/acs/cp)
Hangzhu Senhau Meter Factory
Instrumark International Inc.
Isco Inc. (www.isco.com)
Istec Co.
Johnson Yokogawa Corp.
K & L Research Co. (probe-type)
Krone-America Inc. (www.kanex-krohne.com)
Liquid Controls Inc. (www.lcmeter.com)
Marsh-McBirney Inc. (www.marsh-mcbirney.com)
McCrometer (www.mccrometer.com)
Meter Equipment Mfg.
Metron Technology (insertion-type)
Monitek Technologies Inc. (www.monitek.com)
Montedoro Whitney
MSR Magmeter Manufacturing Ltd. (probe-type)
Nusonics Inc.
Omega Engineering Inc. (www.omega.com)
Oval Corp.
Proces-Data A/S
Rosemount Inc. (www.rosemount.com)
Sarasota Measurements & Controls
Schlumberger Industries (www.s/b.com)
Siemens AG (www.sea.siemens.com)
Signet Industrial (probe-type)
Sparling Instruments Inc. (www.sparlinginstruments.com)
Toshiba International
TSI Flow Meters Ltd. (www.tsi.ie)
Venture Measurement LLC
Wilkerson Instrument Co.
XO Technologies Inc.
Universal Flow Monitors Inc. (www.flowmeters.com)
Yamatake Co.
YCV Co.
Yokogawa Electric Corp. (www.yokogawa.co.uk)

Unlike many other types of flowmeters, magnetic flowmeters offer true noninvasive measurements. They can be constructed easily to the extent that existing pipes in a process can be configured to act as a meter by simply adding two external electrodes and a pair of suitable magnets. They measure both forward and reverse flows. They are insensitive to viscosity, density, and other flow disturbances. Electromagnetic flowmeters are linear devices that are applicable to a wide range of measurements, and they can respond rapidly to changes in the flow. In the recent years, technological refinements have resulted in more economical, accurate, and smaller instruments.

As in the case of many electrical devices, the underlying principle of the magnetic-type flowmeters is 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. This concept is used in electric generators. Faraday foresaw the practical application of this principle to the flow measurements, since many liquids are electrical conductors to some extent. Faraday went farther and attempted to measure the flow velocity of the Thames River. The attempt failed because his instrumentation was not sensitive enough. However, about 150 years later, we successfully can build magnetic flowmeters based on Faraday's law.

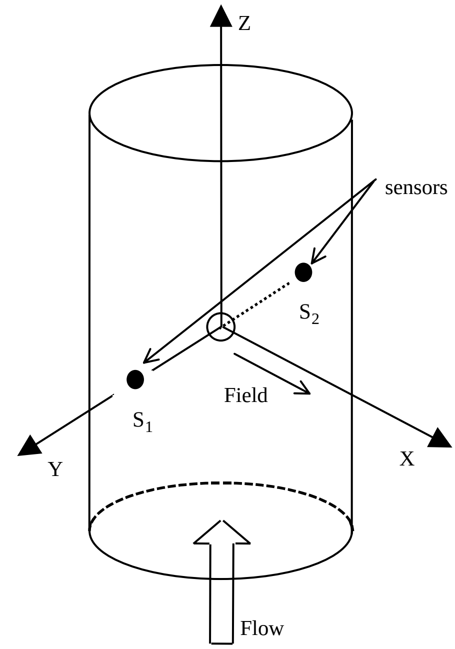


FIG. 2.10a
Operational principle of electromagnetic flowmeters: Faraday's Law states that a voltage is induced in a conductor moving in a magnetic field. In electromagnetic flowmeters, the direction of movement of conductor, the magnetic field and the induced emf are perpendicular to each other in X, Y and Z axes. Sensors S_1 and S_2 experience a virtual conductor due to liquid in the pipe.

THEORY

Faraday's law states that, if a conductor of length l (m) is moving with a velocity v (m/sec) perpendicular to a magnetic field of flux density B (Tesla), a voltage e will be induced across the ends of the conductor. The value of the voltage may be expressed by

$$e = Blv \qquad \textbf{2.10(1)}$$

Figure 2.10a shows how Faraday's law is applied in the electromagnetic flowmeter. The magnetic field, the direction of the movement of the conductor, and the induced emf are all perpendicular to each other. The liquid is the conductor that has a length, D, equivalent to the inside diameter of the flowmeter. The liquid conductor moves with an average velocity V through the magnetic field of strength B. From Equation 2.11(1), the induced voltage e is

$$e = BDV/C \qquad \textbf{2.10(2)}$$

where C is a constant to take care of the proper units.

Figure 2.10b illustrates the principles of operation of electromagnetic flowmeters in detail. When the pair of magnetic coils are energized, a magnetic field is generated in a plane that is mutually perpendicular to the axis of the liquid conductor and the plane of the electrodes. The velocity of the liquid is along the longitudinal axis of the flowmeter body; therefore, the voltage induced within the liquid is mutually perpendicular to both the velocity of the liquid and the magnetic field. The liquid can be considered as an infinite number of conductors moving through the magnetic field, with each element contributing to the voltage generated. An increase in flow rate of the liquid conductors moving through the field will result in an increase in the instantaneous value of the voltage generated. Also, each of the individual "generators" is contributing to the instantaneously generated voltage. Whether the profile is essentially square (characteristic of a turbulent velocity profile), parabolic (characteristic of a laminar velocity profile), or distorted (characteristic of poor upstream piping), the magnetic flowmeter averages the voltage contribution across the metering cross section. The sum of the instantaneous voltages generated is therefore representative of the average liquid velocity, because each increment of liquid velocity within the plane of the electrode develops a voltage proportional to its local velocity. The signal voltage generated is equal to the average velocity almost regardless of the flow profile.

Once the magnetic field is regarded to be constant, and the diameter of the pipe is fixed, the magnitude of the induced voltage will be proportional only to the velocity of the liquid [Equation 2.10(2)]. If the ends of the conductor, in this case the sensors, are connected to an external circuit, the induced voltage causes a current, i, to flow that can be processed suitably as a measure of the flow rate. The resistance of the

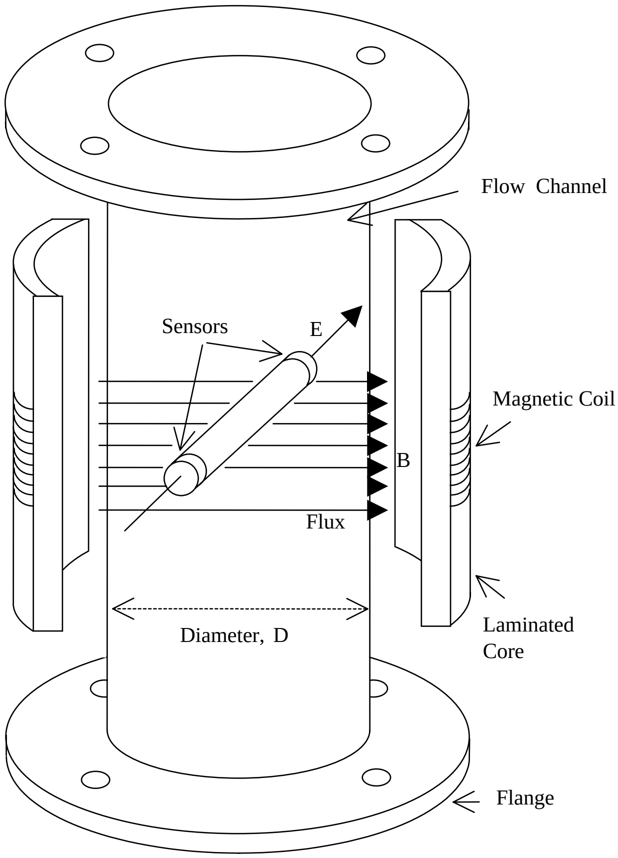


FIG. 2.10b
Construction of practical flowmeters: External electromagnets create a homogeneous magnetic field that passes through the pipe and the liquid inside. Sensors are located 90 deg to the magnetic field and the direction of the flow. Sensors are insulated from the pipe walls. Flanges are provided for fixing the flowmeter to external pipes. Usually, manufacturers supply information about the minimum lengths of the straight portions of external pipes.

moving conductor may be represented by R to give the terminal voltage v_T of the moving conductor as $v_T = e - iR$.

Often, magnetic flowmeters are configured to detect the volumetric flow rate by sensing the linear velocity of the liquid. The relationship between the volume of liquid Q (l/sec) and the velocity may be expressed as

$$Q = Av \qquad \textbf{2.10(3)}$$

Writing the area, A (m^2), of the pipe as

$$A = \pi D^2/4 \qquad \textbf{2.10(4)}$$

gives the induced voltage as a function of the flow rate; that is,

$$e = 4BQ/\pi D \qquad \textbf{2.10(5)}$$

This equation indicates that, in a carefully designed flowmeter, if all other parameters are kept constant, the induced voltage is linearly proportional only to the mean value of the liquid flow. Nevertheless, a main difficulty in electromagnetic flowmeters is that the amplitude of the induced voltage may be very small relative to extraneous voltages and noise. The noise sources include the following:

- Stray voltage in the process liquid
- Capacitive coupling between signal and power circuits
- Capacitive coupling in connection leads
- Electromechanical emf induced in the electrodes and the process fluid
- Inductive coupling of the magnets within the flowmeter

Advantages

1. The magnetic flowmeter is totally obstructionless and has no moving parts. Pressure loss of the flowmeter is no greater than that of the same length of pipe. Pumping costs are thereby minimized.
2. Electric power requirements can be low, particularly with the pulsed DC-types. Electric power requirements as low as 15 or 20 W are not uncommon.
3. The meters are suitable for most acids, bases, waters, and aqueous solutions, because the lining materials selected are not only good electrical insulators but also are corrosion resistant. Only a small amount of electrode metal is required, and stainless steel, Alloy 20®, the Hastelloys®, nickel, Monel®, titanium, tantalum, tungsten carbide, and even platinum are all available.
4. The meters are widely used for slurry services not only because they are obstructionless but also because some of the liners, such as polyurethane, neoprene, and rubber, have good abrasion or erosion resistance.
5. Magmeters are capable of handling extremely low flows. Their minimum size is less than 0.125 in. (3.175 mm) inside diameter. The meters are also suitable for very high-volume flow rates with sizes as large as 10 ft (3.04 m) offered.
6. The meters can be used as bidirectional meters.

Limitations

The meters have the following specific application limitations:

1. The meters work only with conductive fluids. Pure substances, hydrocarbons, and gases cannot be measured. Most acids, bases, water, and aqueous solutions can be measured.
2. The conventional meters are relatively heavy, especially in larger sizes. Ceramic and probe-type units are lighter.
3. Electrical installation care is essential.
4. The price of magnetic flowmeters ranges from moderate to expensive. Their corrosion resistance, abrasion resistance, and accurate performance over wide turndown ratios can justify the cost. Ceramic and probe-type units are less expensive.

5. To periodically check the zero on AC-type magnetic flowmeters, block valves are required on either side to bring the flow to zero and keep the meter full. Cycled DC-units do not have this requirement.
6. An important limitation in electromagnetic flowmeters may be the effect of magnetohydrodynamics, which is especially prominent in fluids with magnetic properties. Hydrodynamics refers to the ability of magnetic field to modify the flow pattern. In some applications, the velocity perturbation due to magnetohydrodynamic effect may be serious enough to influence the accuracy of operations (e.g., in the case of liquid sodium and its solutions).

TYPES OF MAGNETIC FLOWMETERS

There are many different types of electromagnetic flowmeters, all based on Faraday's law of induction, such as the AC, DC, dual-excited, and permanent magnet types. This section concentrates on most commonly used flowmeters: the AC, the DC and the dual-excited types. Classification due to usage is briefly explained in the subsection titled "Other Types."

Modern magnetic flowmeters are also classified as

- Conventional flowmeters
- Smart magnetic flowmeters
- Multivariable magnetic flowmeters

Conventional flowmeters have normally have a 4- to 20-mA output. But these magnetic flowmeters are gradually being phased out because of their limited communication capabilities.

Smart magnetic flowmeters are microprocessor-based devices, and they are capable of communicating digitally with other equipment, such as computers. The communication protocols include HART, FOUNDATION™ fieldbus (FF), Profibus (PB), and serial and parallel communications. Integration of microprocessors give them additional features such as self-diagnostic and self-calibration capabilities. Table 2.10c illustrates communication features of some selected magnetic flowmeters.

Multivariable magnetic flowmeters are capable of measuring more than one process variable. For example, by measuring pressure and temperature, it is possible to calculate

TABLE 2.10c
Communication Capabilities of Modern Magnetic Flowmeters

	Type			*Excitation*		*Communication*			
Company	*Smart*	*Conv*	*Multivar*	*AC*	*DC*	*HART*	*FF*	*Profibus*	*Serial*
ABB	✓			✓	✓	✓	✓	✓	✓
Advanced Flow	✓		✓	✓	✓				✓
Bopp & Reuther	✓	✓			✓			✓	
Brooks Inst.	✓	✓			✓	✓			
Brunata	✓	✓			✓				✓
Danfoss	✓	✓			✓	✓		✓	
Diessel	✓	✓			✓				✓
Elis Pilzen	✓	✓			✓				✓
Endress+Hauser	✓				✓	✓	✓	✓	✓
Foxboro	✓	✓		✓	✓	✓			
Isoil	✓				✓				✓
Krohne	✓			✓	✓	✓	✓	✓	✓
Liquid Controls	✓	✓		✓	✓				✓
McCrometer	✓	✓		✓	✓	✓			✓
Oval	✓	✓			✓	✓			✓
Rosemount		✓			✓	✓	✓		
Siemens		✓		✓	✓	✓			
Sparling Inst.	✓	✓			✓	✓			
Toshiba Intl.	✓	✓			✓	✓			
Venture	✓	✓		✓	✓				✓
Yamatake	✓		✓		✓	✓	✓		
Yokogawa	✓				✓	✓	✓		

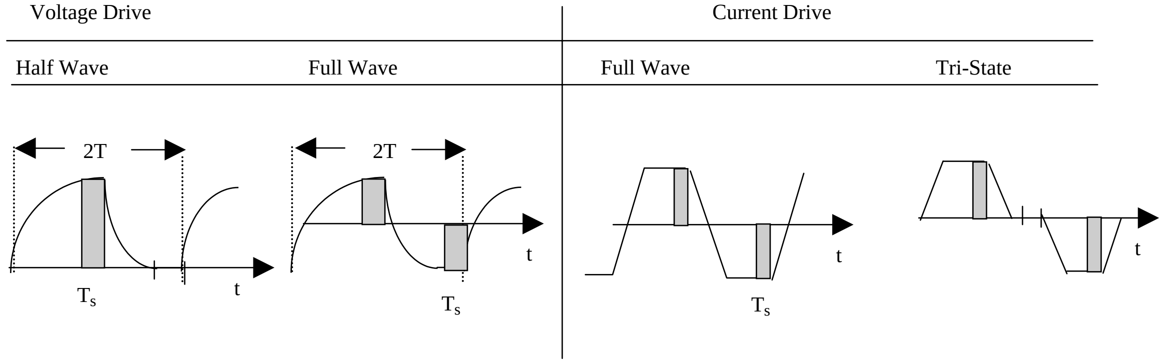


FIG. 2.10d
Types of pulsed DC coil excitation.

density of the flowing materials. From the density, mass flow can be determined.

AC Magnetic Flowmeters

In many commercial magnetic flowmeters, an alternating current of 50 or 60 Hz creates the magnetic field in coils to induce voltage in the flowing liquid. The signals generated are dependent on the velocity of liquid and flowmeter dimensions. Generally, they resemble low-level AC signals, being in the high microvolt to low millivolt ranges. A typical value of the induced emf in an AC flowmeter fixed on a 50 mm internal diameter pipe carrying 500 l/min is observed to be about 2.5 mV.

The AC excitations may be in different forms, but generally they can be categorized into two families: those using on–off excitation and those using plus–minus excitation. In either case, the principle is to take a measurement of the induced voltage when the coils are not energized and to take a second measurement when the coils are energized and the magnetic field has stabilized. Figure 2.10d shows some of the types of excitation offered by various manufacturers.

AC flowmeters operating 50, 60, or 400 Hz are readily available. In general, AC flowmeters can operate from 10 Hz to 5000 Hz. High frequencies are preferred in determining the instantaneous behavior of transients and pulsating flows. Nevertheless, in applications where extremely good conducting fluids and liquid metals are used, the frequency must be kept low to avoid skin effect. On the other hand, if the fluid is a poor conductor, the frequency must not be so high that dielectric relaxation is not instantaneous.

AC magnetic flowmeters reduce the polarization effects at the electrodes, and they are less affected by the flow profiles of the liquid in the pipe. They allow the use of high-Z_{in} amplifiers with low drift and highpass filters to eliminate slow and spurious voltage drifts emanating mainly from thermocouple and galvanic actions. These flowmeters find many diverse applications, including measurement of blood flow in living specimens. Miniaturized sensors allow measurements on pipes and vessels as small as 2 mm dia. In these applications, the excitation frequencies are higher than industrial types—200 to 1000 Hz.

A major disadvantage of an AC flowmeter is that the powerful AC field induces spurious AC signals in the measurement circuits. This requires periodic adjustment of zero output at zero-velocity conditions, which is more frequent than in DC counterparts. Also, in some harsh industrial applications, currents in the magnetic field may vary due to voltage fluctuations and frequency variations in the power lines. The effect of fluctuations in the magnetic field may be minimized by the use of a reference voltage proportional to the strength of the magnetic field to compensate for these variations. To avoid the effects of noise and fluctuations, special cabling and calibration practices recommended by the manufacturers must be used to ensure accurate operations. Usually, the use of two conduits is required—one for signals and one for power. The cable lengths also should be set to specific levels to minimize noise and sensitivity problems.

DC Magnetic Flowmeters

Unlike AC magnetic flowmeters, direct current or pulsed magnetic flowmeters excite the flowing liquid with a magnetic field operating at 3 to 8 Hz. In all of the pulsed DC approaches, the concept is to take a measurement when the coils are excited and store (hold) that information, then take a second measurement of the induced voltage when the coils are not excited (Figure 2.10d). As the current to the magnet is turned on, a DC voltage is induced at the electrodes. When the current in the magnetic coils is turned off, the signal represents only the noise. The signals observed at the electrodes represent the sum of the induced voltage and the noise, as illustrated in Figure 2.10e. Subtracting the measurement of the flowmeter when no current flows through the magnet from the measurement when current flows through the magnet effectively cancels out the effect of noise.

When the magnetic field coils are energized by a normal direct current, several problems occur, such as polarization and electrochemical and electromechanical effects. Polarization is the formation of a layer of gas around the measured electrodes. Some of these problems may be overcome by

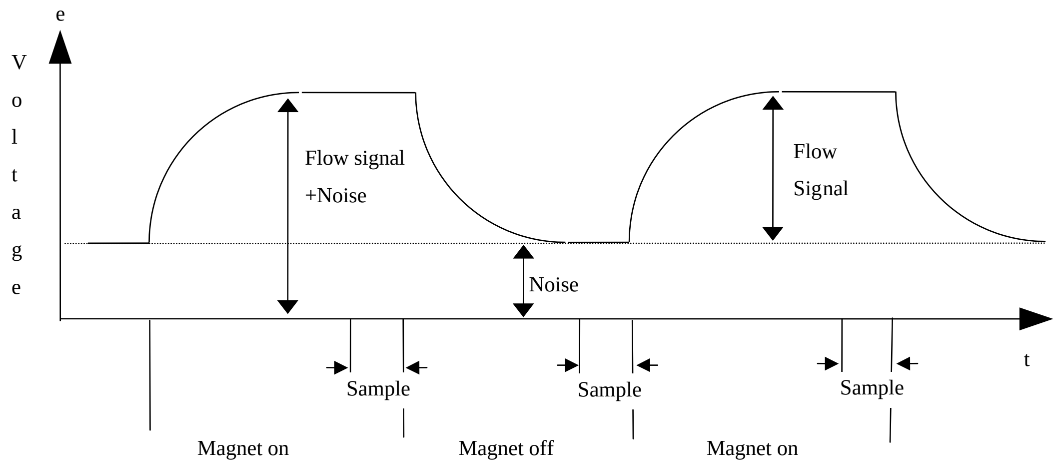


FIG. 2.10e
Signal development of pulsed DC-type magnetic flowmeter with half-wave excitation. As shown, the magnetic field is generated by a square wave which, in function, turns the magnet "on" and "off" in equal increments. When "on," the associated signal converter measures and stores the signal which is a composite of flow plus a variable (non-flow-related) residual voltage. During the "off" period, the converter measures the variable (non-flow-related) residual signal only. Since no field excitation is present, no flow signal will be generated. The converter then subtracts the stored residual signal from the flow developed-plus residual signal, resulting in the display of a pure flow signal.

energizing the field coils at higher frequencies. However, higher frequencies generate transformer action in the signal leads and in the fluid path. Therefore, the coils are excited by DC pulses at low repetition rates to eliminate the transformer action. In some flowmeters, by appropriate sampling and digital signal processing techniques, the zero errors and the noise can be rejected easily.

The pulsed DC-type systems establish zero during each on–off cycle. This occurs several times every second. Because zero is known, the end result is that pulsed DC systems are potential percent-of-rate systems. The AC-type systems must be periodically rezeroed by stopping flow and maintaining a full pipe so as to zero out any voltage present at that time.

The zero compensation inherent in the DC magnetic flowmeters eliminates the necessity of zero adjustment. This allows the extraction of flow signals regardless of zero shifts due to spurious noise or electrode coating. Unlike AC flowmeters, larger insulating electrode coating can be tolerated that may shift the effective conductivity significantly without affecting performance. As effective conductivity remains sufficiently high, a DC flowmeter will operate satisfactorily. Therefore, DC flowmeters are less susceptible to drifts, electrode coatings, and changes in the process conditions as compared with conventional AC flowmeters.

As a result of the slow, pulsed nature of their operations, DC magnetic flowmeters do not have good response times. However, so long as there are not rapid variations in the flow patterns, zero to full-scale response times of a few seconds do not create problems in most applications. Power requirements are also much less, because the magnet is energized only part of the time. This gives power savings of up to 75%.

If the DC current to the magnet is constant, the proportional magnetic field may be kept steady. Therefore, the amplitudes of the DC voltages generated at the electrodes will be linearly proportional to the flow. However, in practice, the current to the magnet varies slightly due to line voltage and frequency variations. As in the case of AC flowmeters, voltage and frequency variations may require the use of a reference voltage. Because the effect of noise can be eliminated more easily; the cabling requirements are not as stringent.

As mentioned before, polarization may be a problem in DC-type flowmeters. To avoid electrolytic polarization of the electrodes, bipolar pulsed DC flowmeters are available. Also, modification of the DC flowmeters has led to the development of miniature DC magnetic flowmeters that use wafer technology for a limited range of applications. The wafer design reduces weight and power requirements.

Dual-Frequency Excitation

Changing the method of excitation from line frequency (AC) to low frequency (DC) provided dramatic improvements in both the accuracy and the zero stability of magnetic flowmeters. Yet it did not represent the summit in technological advancements. A limitation of low-frequency (DC) designs is their relatively low response speed (0.2 to 2 sec) and their sensitivity to measurement noise caused by slurries or low-conductivity fluids.

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. This is achieved by exciting the magnetic field coils by a current with such a compound wave, as illustrated in Figure 2.10f. One component is a low-frequency waveform, much below 60 Hz, which guarantees good

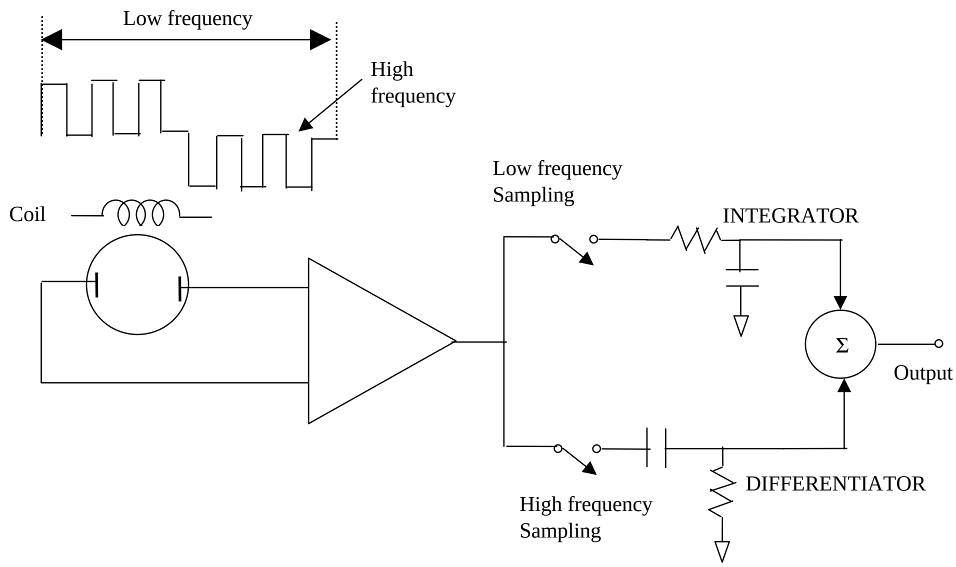


FIG. 2.10f
Dual-frequency excitation design combines the advantages of both systems.

zero stability. The output generated by the low-frequency signal is integrated via a long time constant to provide a smooth and stable flow signal.

The high-frequency component is superimposed on the low-frequency signal to provide immunity to noise caused by low conductivity, viscosity, slurries, and electrochemical reactions. The output generated by the high-frequency component is sampled at a high frequency and is processed in a differentiating circuit having the same time constant as the integrating circuit. By adding the two signals, the result is an output that is free of "slurry" noise and has good zero stability plus good response speed.

Other Types

Classification of magnetic flowmeters varies from one manufacturer to the next. A typical classification involves several types: wafer, flange, partially filled, micro-fractional, large-size, and sanitary. There are variations in the size of detectors and other features made suitable for a specific application. For example, micro-fractional detectors are designed to measure small amounts of fluids containing substances such as chemicals. The wetted materials are made from corrosion-resistant ceramic and platinum. They are lightweight, palm-size detectors suitable for use in 2.5-mm pipes. In contrast, in large-size types, the coils are arranged to measure uneven flows, and the flowmeters are made with improved noise suppression. The size can be as large as 3000 mm (120 in.).

CONSTRUCTION OF MAGNETIC FLOWMETERS

Figure 2.10g is a cutaway view showing how the principle of electromagnetic induction is employed in a practical flowmeter. The basic element of the flowmeter is a section of

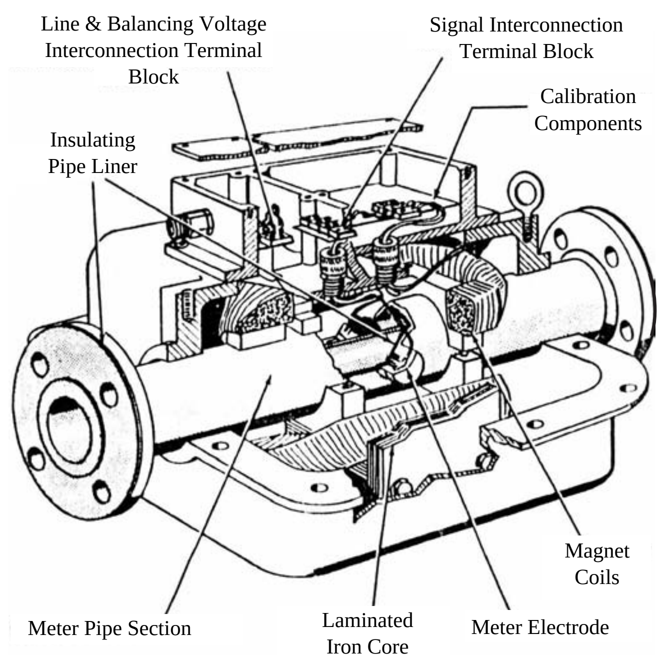


FIG. 2.10g
Cutaway view of the magnetic flowmeter.

nonconducting pipe such as glass-reinforced polyester or a nonmagnetic pipe section lined with an appropriate electrical conductor such as Teflon, Kynar, fiberglass, vitreous enamel, rubber, neoprene, or polyurethane, among others. On alternate sides of the pipe section are magnet coils that produce the magnetic field perpendicular to the flow of liquid through the pipe. Mounted in the pipe, but insulated from it and in contact with the liquid, is a pair of electrodes that are located at right angles both to the magnetic field and the axis of the pipe.

As the liquid passes through the pipe section, it also passes through the magnetic field set up by the magnet coils, inducing a voltage in the liquid; the amplitude of the voltage is directly proportional to the liquid velocity. This voltage is conducted by the electrodes to a separate converter that, in effect, is a precision voltmeter (electrometer) capable of accurately measuring the voltage generated and converting that voltage to the desired control signals. These may be equivalent electronic analog signals, typically 4 to 20 mA DC, or a frequency or scaled pulse output.

Most electromagnetic flowmeters are built with flanged end fittings, although the insert types are also common. Designs are available with sanitary-type fittings. In large pipe sizes, Dresser-type and Victaulic-type end connections are also widely used. Some electromagnetic flowmeters are made from replaceable flow tubes whereby the field coils are located external to the tubes. In these flowmeters, the flanges are located far apart so as to reduce their adverse effects on the accuracy of measurements; hence, they are relatively large in dimension. In others, the field coils are located closer to the flow tube or even totally integrated. In this case, the flanges could be located closer to the magnets and the electrodes, thus giving relatively smaller dimensions. On the other hand, the miniature and electrodeless magnetic flowmeters are so compact in size that face-to-face dimensions are short enough to allow them to be installed between two flanges.

The pipe between the electromagnets of a flowmeter must be made from nonmagnetic materials to allow the field to penetrate the fluid without any distortion. Therefore, the flow tubes are usually constructed of stainless steel or plastic. The use of steel is a better option, since it adds strength to the construction. Flanges are protected with appropriate liners, and they do not make contact with the process fluid.

The electrodes for the magnetic flowmeters must be selected such that they will not be coated with insulating deposits of the process liquid during long periods of operations. The electrodes are placed at positions where maximum potential differences occur. They are electrically isolated from the pipe walls by nonconductive liners to prevent short-circuiting of electrode signals. The liner also serves as protection to the flow tube to eliminate galvanic action and possible corrosion due to metal contacts. Electrodes are held in place by holders that also provide sealing. In some flowmeters, electrodes are cleaned continuously or periodically by ultrasonic or electrical means. Ultrasonics are specified for AC- and DC-type magnetic flowmeters when frequent severe insulating coating is expected on the electrodes that might cause the flowmeter to cease to operate in an anticipated manner.

Versions of magnetic flowmeters are available for periodic accidental submergence and for continuous submergence in water at depths of up to 30 ft (9 m). An outgrowth of the continuous submergence design is a sampling type (pitot). The pitot-type magnetic flowmeter samples the flow velocity in large rectangular, circular, or irregularly shaped

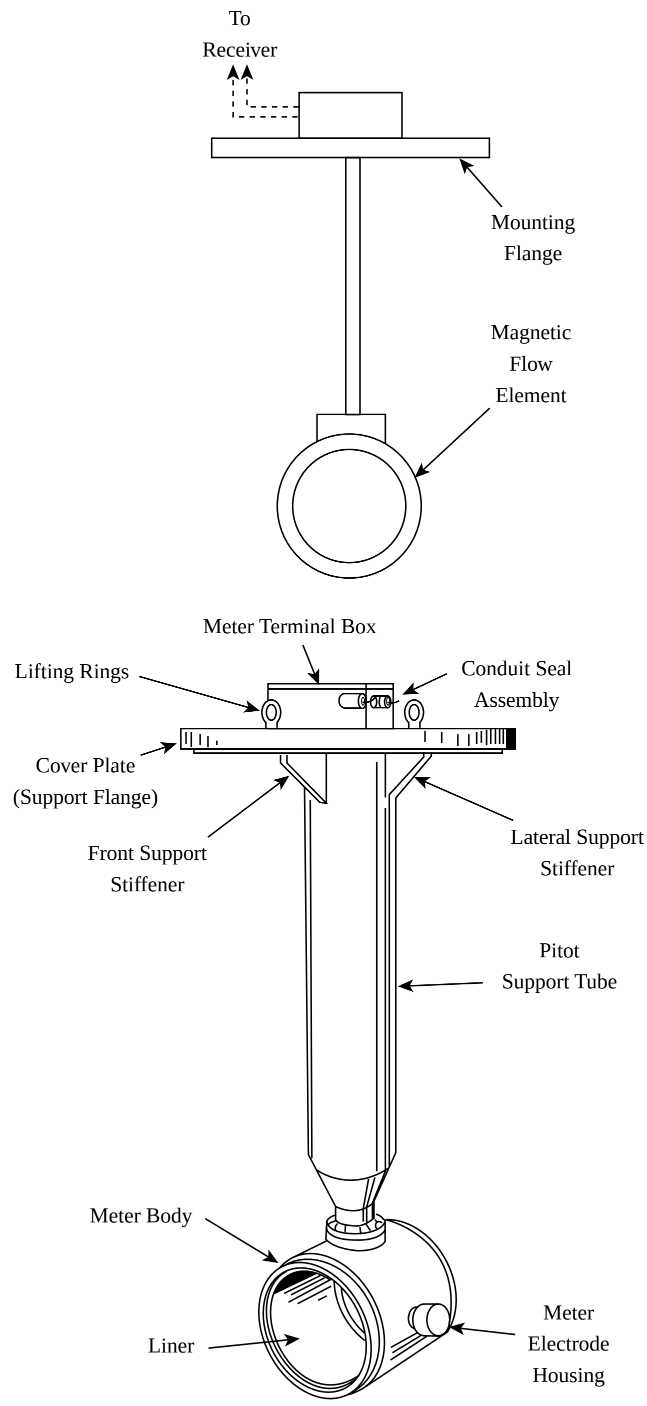


FIG. 2.10h
Pitot-type magnetic flowmeter.

pipes or conduits. A typical design is shown in Figure 2.10h. A small magnetic flowmeter is suspended in the flow stream. The magnet coils are completely encapsulated in the liner material, allowing submersion in the liquid to be measured. The short length of the meter body and the streamlined configuration are designed to minimize the difference between the flow velocity through the meter and the velocity of the liquid passing around the meter. The velocity measurement

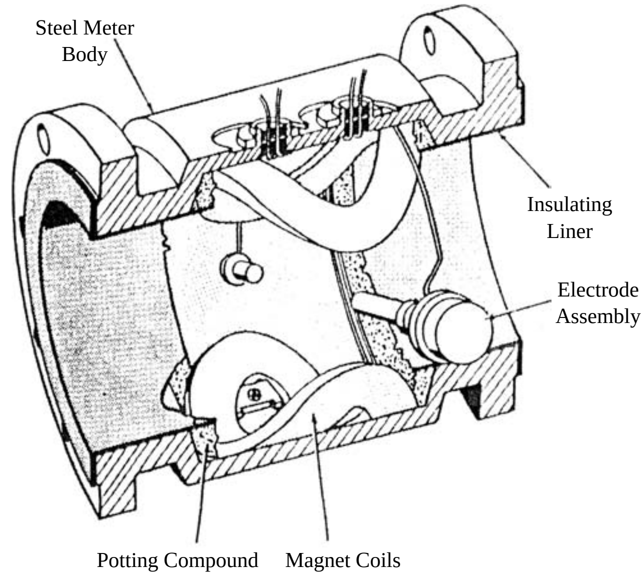


FIG. 2.10i
The short-form magnetic flowmeter.

of the liquid through the meter is assumed to be representative of the pipe velocity. Repeatability of the system is typically 0.25 to 0.5% of full scale. As with any sampling-type flowmeter, the information from the flowmeter is representative only of the flow through the flowmeter. It is the user's responsibility to relate that "sampled" velocity to the average velocity in the pipe, which reflects the total volumetric flow rate. When applying any sampling-type flowmeter, including the pitot-type magnetic flowmeter, substantial errors can occur in applications where the velocity profile can change due to changes in Reynolds number or due to the effects of upstream piping configuration.

Most manufacturers construct their flowmeters with coils external to the meter pipe section. Some designs place the coils within the flowmeter body, which is made from carbon steel to provide the return path for the magnetic filed as in Figure 2.10i. In this design, the meters can be shorter, have reduced weight, and offer lower power consumption. The lowest power consumption is a feature of the pulsed DC design, because its coils are energized only part of the time. An additional saving with pulsed DC types is that the power factor approaches 1.

Ceramic Liners

The use of ceramic liners represents a major improvement in the design of magnetic flowmeters, because they cost less to manufacture and also provide a better meter. Ceramic materials such as Al_2O_3 are ideal liner materials, because their casting is inexpensive, they are electrically nonconductive, and they are abrasion- and wear-resistant. In contrast with plastic liners, they can be used on abrasive slurry services (pipelining of minerals or coal), and their inner surfaces can be scraped with wire brushes to remove hardened coatings. Ceramic units are also preferred for sanitary applications because they do not provide any cavities in which bacteria can accumulate and grow. Ceramic meters can also handle higher temperatures (360°F, 180°C) than Teflon-lined ones (250°F, 120°C). Magnetic flowmeters are velocity sensors and, to convert velocity into volumetric flow rate, the pipe cross section has to be constant. Therefore, the ceramic liners have the added advantage of expanding and contracting less with changes in temperature than do metals or plastics. Ceramic liners are also preferred by the nuclear industry because they are not affected by radiation, whereas plastics are destroyed by it.

The design of the ceramic insert-type magnetic flowmeter also eliminates the possibility of leakage around the electrodes. This perfect seal is produced by allowing a droplet of liquid platinum to sinter through the ceramic wall of the liner. Through this process, the ceramic particles and the platinum fuse into a unified whole, providing not only a perfect seal but also a permanent, rugged, and corrosion-resistant electrode. This electrode cannot move, separate, or leak.

For the reasons listed above, the ceramic insert-type magnetic flowmeter is an improvement. However, it also has some limitations. One of its limitations has to do with its brittle nature. Ceramic materials are strong in compression but should not be exposed to pipe forces that cause tension or bending. Another possible way to crack the ceramic lining is by sudden cooling. Therefore, these elements should not be exposed to downward step changes in temperature that exceed 90°F (32°C). Another limitation of the Al_2O_3 ceramic liner is that it cannot be used with oxidizing acid or hot, concentrated caustic applications (over 120°F, 50°C).

Probe-Type Units

The probe-type magnetic flowmeter is an "inside out" design in the sense that the excitation coil is on the inside of the probe, as shown in Figure 2.10j. As the process fluid passes through the magnetic field generated by the excitation coil inside the probe, a voltage is detected by the electrodes that are embedded in the probe. The main advantage of this design is its low cost, which is not affected by pipe size, and its retractable nature, which makes it suitable for wet-tap installations. The probe-type magmeter is also suited for the measurement of flow velocities in partially full pipes or in detecting the currents in open waters. When water flow is not constrained by a pipe, flow velocity has to be expressed as a three-dimensional vector. By inserting three magmeter probes parallel with the three axes, one can detect that vector.

The main disadvantage of the magmeter probe is that it detects the flow velocity in only a small segment of the cross-sectional area of the larger pipe. Therefore, if the flowing velocity in that location is not representative of the rest of the cross section, a substantial error can result.

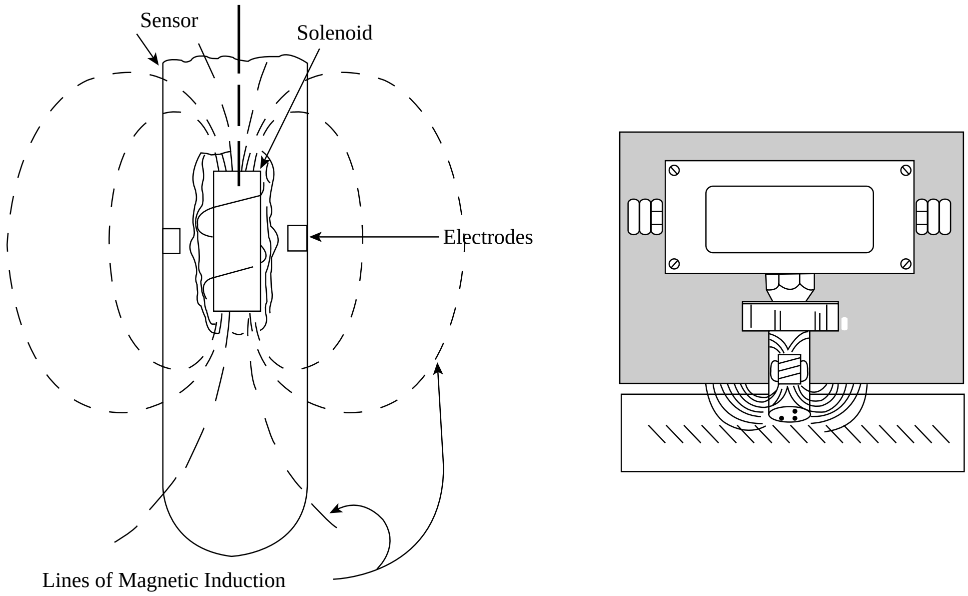


FIG. 2.10j
The probe-type magnetic flowmeter.

TABLE 2.10k
Sizes and Capacities of Commonly Used Electromagnetic Flowmeters

Meter Size (mm)	Dimensions (mm)	Weight (kg)	Flow Rate (m^3/h) 0.3 m/s	1.0 m/s	10 m/s	Standard Flow Range m^3/h	m/s
15	70 × 180 × 50	3	0.191	0.636	6.360	2	3.125
25	80 × 170 × 65	3	0.530	1.770	17.67	6	3.400
40	100 × 240 × 85	6.5	1.357	4.525	45.25	15	3.315
50	110 × 260 × 100	7	2.120	7.067	70.67	25	3.540
80	110 × 280 × 125	8	5.428	18.10	180.9	60	3.315
100	120 × 315 × 160	10	8.482	28.30	282.7	100	3.540
150	230 × 390 × 215	22	19.10	63.61	636.1	200	3.125
200	300 × 440 × 270	36	33.90	113.1	1131.0	300	2.655

APPLICATIONS OF MAGNETIC FLOWMETERS

In the applications of magnetic flowmeters, a number of considerations must be taken into account, including the following:

- Cost, simplicity, precision, and reproducibility
- Metallurgical aspects
- Velocity profiles and upstream disturbances

During the selection of electromagnetic flowmeters, the size of the required flowmeter, the process characteristics and existing structure, and the velocity constraints should be evaluated carefully to secure accurate performance over the expected range. Table 2.10k illustrates the typical sizes and capacities of most commonly available flowmeters. The full-scale velocity of the flowmeter is typically 0.3 to 10 m/sec. Some flowmeters can measure lower velocities, with somewhat poorer accuracy. Generally, employment of electromagnetic flowmeters over a velocity of 5 m/sec should be considered carefully, since erosion of the pipe and the damage to liners can be significant. In all applications, determining the size of the flowmeter is a matter of selecting the one that can handle the liquid velocities. The anticipated liquid velocity must be within the linear range of the device. The capacities of various sizes of flowmeters are given in Figure 2.10l as a typical guide for selection.

Magnetic flowmeters are the first to be considered for very corrosive applications and for applications involving measurement of abrasive and/or erosive slurries. They are widely used in pulp and paper stock measurement and other non-Newtonian applications. They can be used for very low flow rates; pipe inside diameters as small as 0.1 in. (2.5 mm) are offered that can handle flow ranges as low as 0.01 to 0.1 GPM (0.038 to 0.38 l/min). Magnetic flowmeters are also available in pipe sizes up to 120 in. (3 m).

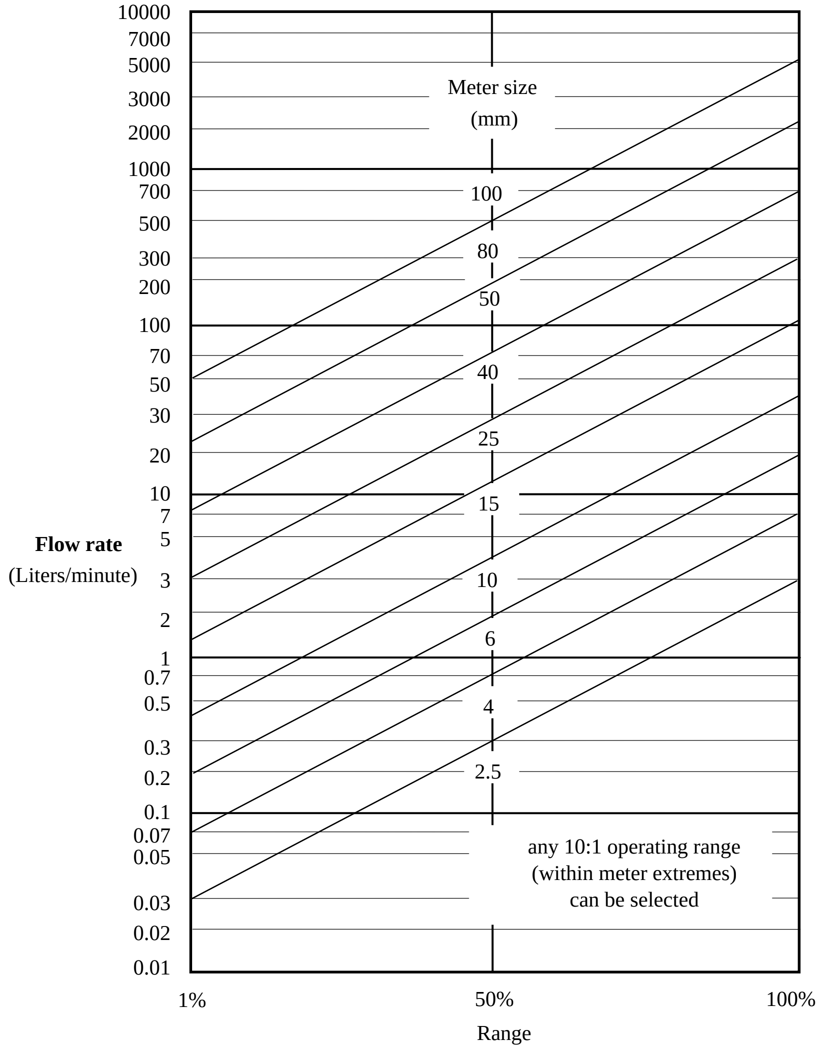


FIG. 2.10l

Selection of flowmeters: In the selection of a suitable flowmeter for a particular application care must be exercised for handling the anticipated liquid velocities. The velocity of liquid must be within the linear range of the device. For example, a flowmeter with 100 mm internal diameter can handle flows between 50 L/min to 4000 L/min. An optimum operation will be achieved at flow-rate of 500 L/min.

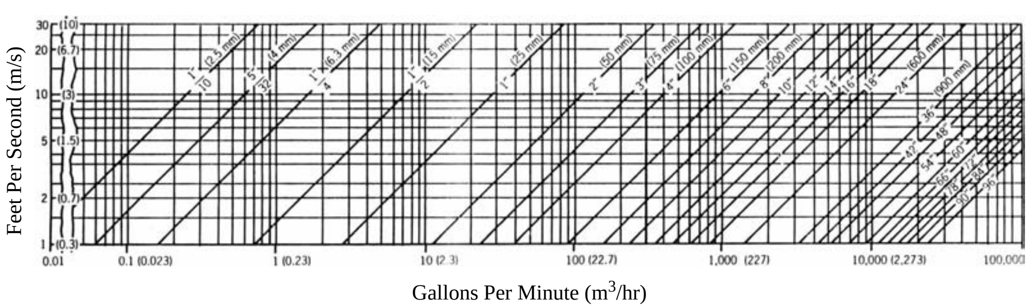


FIG. 2.10m

Magnetic flowmeter capacity nomograph.

Figure 2.10m is a nomograph for magnetic flowmeter capacities. Magnetic flowmeters have an excellent operating range of at least 100:1. For AC types, typical inaccuracy is ±1% of full scale. To improve performance, range is usually divided into two portions and automatically switched between the two. Pulsed DC-types have typical inaccuracy of ±1% of rate applicable to a 10:1 range or ±0.5% of rate over a 2:1 or 5:1 range, and at flow rates below 10% of maximum it is on the order of ±0.1% of full scale. The converter can be set for 20 mA output at any flow between 10 and 100% of meter capacity and still have at least a 10:1 operating range. This ability to field set or reset the meter for the actual operating conditions provides optimal performance.

Most processes employ circular piping that adds simplicity in the construction of the system. The flowmeters connected to circular pipes give relatively better results as compared to rectangular or square-shaped pipes, and velocity profiles of the liquid are not affected by the asymmetry. However, in circular pipes, the fringing of the magnetic field may be significant, making it necessary to employ empirical calibrations.

Upstream and downstream straight piping requirements may vary from one flowmeter to another, depending on the manufacturer's specifications. As a rule of thumb, the straight portion of the pipe should be at least 5D/2D from the electrodes and 5D/5D from the face of the flowmeter in upstream and downstream directions, respectively. For a good accuracy, the recommendations of manufacturers for piping requirements should be carefully observed. In some magnetic flowmeters, coils are used in such a way that the magnetic field is distributed in the coil to minimize the piping effect.

Magnetic flowmeters are often used to measure explosive fluids in hazardous environments. In these applications, explosion-proof housings are absolutely essential. The construction and specifications of such housings are regulated by authorities such as the European Committee for Electrotechnical Standardization (CENELEC). Usually, integral or remote electronics are offered for mounting flexibility and reliability. In many instruments, the electronic circuitry is separated from field wiring terminations by a dual-compartment housing and an integral backlit LCD design that provides an easy operator interface.

Accuracy and Calibration

The power consumption of a conventional (high-frequency AC excited) 2-in. (50-mm) flowmeter is about 30 W. For a 30-in. (76-cm) flowmeter, it is about 300 W. Low-frequency DC excitation has reduced the power consumption of some magnetic flowmeters to 20 W, regardless of meter size. The accuracy of conventional magnetic flowmeter is usually expressed as a function of full scale, typically 0.5 to 1% FS. However, DC flowmeters have a well-defined zero due to an automatic zeroing system; therefore, they have percentage rate of accuracy better than AC types (typically 0.5 to 2%).

Magnetic flowmeters do not require continuous maintenance other than periodic calibrations. Nevertheless, electrode coating, damage to the liners, and electronic failures may occur. Any modifications and repairs must be treated carefully because, when installed again, some accuracy may be lost. After each modification or repair, recalibration may be necessary.

Calibration of electromagnetic flowmeters is achieved with a magnetic flowmeter calibrator or by electronic means. The magnetic flowmeter calibrators are precision instruments that inject simulated output signals of the primary flowmeter into the transmitter. Effectively, this signal is used to check correct operation of electronic components and make adjustments to the electronic circuits. Alternatively, calibrations can also be made by injecting suitable test signals to discrete electronic components. In some cases, empirical calibrations must be performed at zero flow while the flowmeter is filled with the stationary process liquid.

Zero adjustment of AC magnetic flowmeters requires compensation for noise. If the zero adjustment is performed with a fluid other than process fluid, serious errors may result because of possible differences in conductivities. Similarly, if the electrodes are coated with an insulating substance, the effective conductivity of the electrodes may be altered, causing a calibration shift. If the coating changes with time, the flowmeter may continually require calibration for repeatable readings.

Errors in Magnetic Flowmeters

Operation of a magnetic flowmeter is generally limited by factors such as liner characteristics, pressure ratings of flanges, and temperatures of the process fluids. The maximum temperature limit is largely dependent on the liner material selection and usually is set to around 120°C. For example, the ceramic liners can withstand high temperatures but are subject to cracking subjected to sudden temperature changes in the process fluid.

For accurate measurements, magnetic flowmeters must be kept full of liquid at all times. If the liquid does not contact the electrodes, no measurements can be taken. Figure 2.10n illustrates this point. If the measurements are made in flows other than vertical, the electrodes should be located in horizontal directions to eliminate the possible adverse effect of the air bubbles, given that air bubbles tend to concentrate on the top of the liquid.

Often, the magnetic flowmeter liners are damaged by the presence of debris and solids in the process liquid. Also, the use of incompatible liquid with the liners, wear due to abrasion, and excess temperature during installations and removals can contribute to the damage of liners. The corrosion in the electrodes

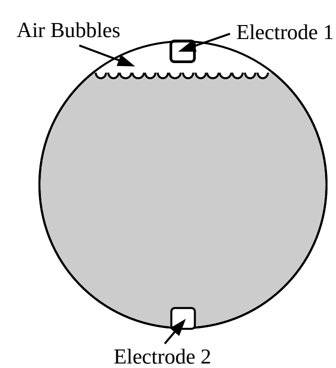


FIG. 2.10n
The pipes of electromagnetic flowmeters must be full of liquid at all times for accurate measurements. If the liquid does not make full contact with electrodes the high impedance prevents the current flow hence measurements cannot be taken. Also, If the pipe is not full, even if contact is maintained between the liquid and electrodes, the empty portions of the pipe will lead to miscalculated flow rates.

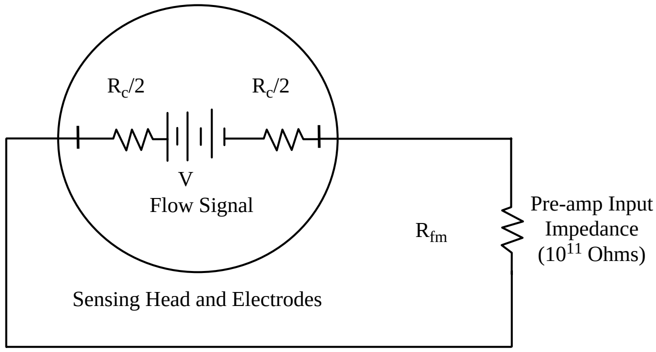


FIG. 2.10o
Increased flowmeter impedance (R_{fm}) reduces coating error.

may also be a contributing factor for the damage. In some cases, magnetic flowmeters may be repaired on site if severe damage occurs; in others, they must be shipped to the manufacturer for repairs. Usually, manufacturers supply spare parts for electrodes, liners, flow tubes, and electronic components.

Grease and other nonconductive electrode coatings introduce an error in the measurement, because the voltage generated by the conductive fluid is measured by the magmeter electronics as a voltage drop across its input impedance R_{fm} as in Figure 2.10o. When there is an electrically resistant coating on the electrodes, some of the voltage generated by the conductive liquid drops across the coating, and less of it remains to be detected by the input impedance. The resulting error percentage can be calculated as follows:

$$E = 100R_c/(R_{fm} + R_e) \qquad \textbf{2.10(6)}$$

Coating resistance (R_c) can reach 10^7, and if the input impedance (R_{fm}) in similar, substantial errors will result. In some newer designs, the input impedance of the flowmeter has been increased to $R_{fm} = 10^{11}$. Even at a coating impedance of $R_c = 10^7$, this limits the coating error to 0.01%. With such high-impedance electronics, the need for electrode cleaning is minimized or eliminated.

The meter's electrodes must remain in electrical contact with the fluid being measured and should always be installed in the horizontal plane. In applications where a buildup or coating of the inside wall of the flowmeter occurs, periodic "flushing" or cleaning is recommended. Coatings can have conductivities that are the same, lower, or higher than the liquid. These effects are significantly different. Where the conductivity of the coating is essentially the same as that of the liquid, there is no effect on the accuracy of the measurement except for the effect of a reduced cross-sectional area. This can be viewed as a specific profile condition, and the meter will average the velocity to give the correct value for the particular flow rate. Fortunately, this is the most common coating condition. If the conductivity of the coating is significantly lower than that of the liquid being measured, the electrically insulating coating can disable the meter. If periodic cleaning is not possible, mechanical, ultrasonic, thermal, and other electrode cleaning techniques can be applied. Manufacturers also offer specifically shaped protruding electrodes to take advantage of the self-cleaning effect of the flow at the electrode. If the conductivity is higher than that of the process fluid, no corrective measure is needed.

EFFECTS OF ELECTRICAL CONDUCTIVITY OF FLUID

For electromagnetic flowmeters to operate accurately, the process liquid must have minimum conductivity of about 1 to 5 μS/cm. Most common applications involve liquids whose conductivity is greater than 5 μS/cm. Nevertheless, for accurate operations, the requirement for the minimum conductivity of liquid can be affected by length of leads from sensors to transmitter electronics. For example, the resistance between electrodes may be approximated by $R = 1/\delta d$, where δ is the fluid conductivity and d is the electrode diameter. For tap water, $\delta = 200$ μS/cm, for gasoline $\delta = 0.01$ μS/cm, and for alcohol 0.2 μS/cm. A typical electrode with a 0.74-cm diameter in contact with tap water results in a resistance of 6756 Ω.

Application of magnetic flowmeters can be realized only with conductive liquids such as acids, bases, slurries, foods, dyes, polymer emulsions, and suitable mixtures that have conductivities greater than the minimum conductivity requirements. Generally, magnetic flowmeters are not suitable for liquids containing organic materials and hydrocarbons. As a rule of thumb, magnetic flowmeters can be applied if the process liquids constitute a minimum of about 10% conductive liquid in the mixture.

Most liquids or slurries are adequate electrical conductors to be measured by electromagnetic flowmeters. If the liquid conductivity is equal to 20 μS/cm or greater, most of the conventional magnetic flowmeters can be used. Special designs are available to measure the flow of liquids with threshold conductivities as low as 0.1 μS/cm. Some typical electrical conductivities are as shown in the following table.

Liquid (at 25°C except where noted)	*Conductivity, μS/cm*
Acetic acid (up to 70% by weight)	250 or greater
Ammonium nitrate (up to 50% by weight)	360,000 or greater
Molasses (at 50°C)	5000
Ethyl alcohol	0.0013
Formic acid (all concentrations)	280 or greater
Glycol	0.3
Hydrochloric acid (up to 40% by weight)	400,000 or greater
Kerosene	0.017
Magnesium sulfate (up to 25% by weight)	26,000 or greater
Corn syrup	16
Phenol	0.017
Phosphoric acid (up to 87% by weight)	50,000 or greater
Sodium hydroxide (up to 50% by weight)	40,000 or greater
Sulfuric acid (up to 99.4% by weight)	8500 or greater
Vodka (100 proof)	4
Water (potable)	70

The effect of conductivity changes above the threshold conductivity may be minimal, but the effect of liquid operating temperature on the threshold conductivity should be considered. Most liquids have a positive temperature coefficient of conductivity. Liquids that are marginal at one temperature can become nonconductive enough at a lower temperature to impair metering accuracy. At a higher temperature, the same liquid may be metered with good results. There are a few liquids that have a negative temperature coefficient; these should be carefully checked for their minimum conductivity before applying magnetic flowmeters.

Magnetic flowmeters are not affected by viscosity or consistency (referring to Newtonian and non-Newtonian fluids, respectively). The changes in flow profile resulting from changes in Reynolds numbers, or from upstream piping, do not greatly affect the performance of magnetic flowmeters. The voltage generated is a summation of the incremental voltages across the entire area between the electrodes, resulting in a measure of the average fluid velocity. Nevertheless, it is recommended to install the meter with 5 diameters of straight pipe before it and 3 diameters of straight pipe following it.

INSTALLATION

The signal detected by magnetic flowmeter electrodes is in the high microvolt to low millivolt range. Proper electrical installation and grounding is mandatory. Individual manufacturer's recommendations for installation are the result of extensive experience and should be scrupulously followed, as illustrated in Figure 2.10p.

Alternating-current-type magnetic flowmeters occasionally shift their no-flow indication after some operating time, requiring a zero reset. One of the most important installation considerations with electromagnetic flowmeters is a proper *bonding* of the flowmeter to the adjacent piping to minimize zero shifts. The intent of this bonding, or *jumpering*, is to prevent stray currents from passing through the flowmeter near the electrodes. Magnetic flowmeters are lined with an electrically insulating material; generally, this lining covers the flange face of the meter, making the meter an electrical discontinuity in the system. The flange bolts should not be used for bonding, given that rust, corrosion, paint, and other insulating materials can create an insulating barrier between the bolts and the flanges. Manufacturers supply, and insist on, the installation of copper braid jumpers from the meter flange to the pipe flange at either end of the flowmeter. The jumpers provide a continuous path for the stray currents, which guarantees a more stable zero. It is also essential to install a ground strap to a grounded piece of structural steel, a grounding rod, or a conductive cold water pipe.

We can eliminate the above-described installation process, which involves labor-intensive drilling, tapping, and strapping of adjacent pipe flanges in metallic pipes or the installation of expensive grounding rings in lined or nonconductive pipes, if the magmeter is provided with built-in grounding electrodes. When installing the flowmeter, the grounding electrode must always be at the bottom and must be connected to the third-wire ground of the power input.

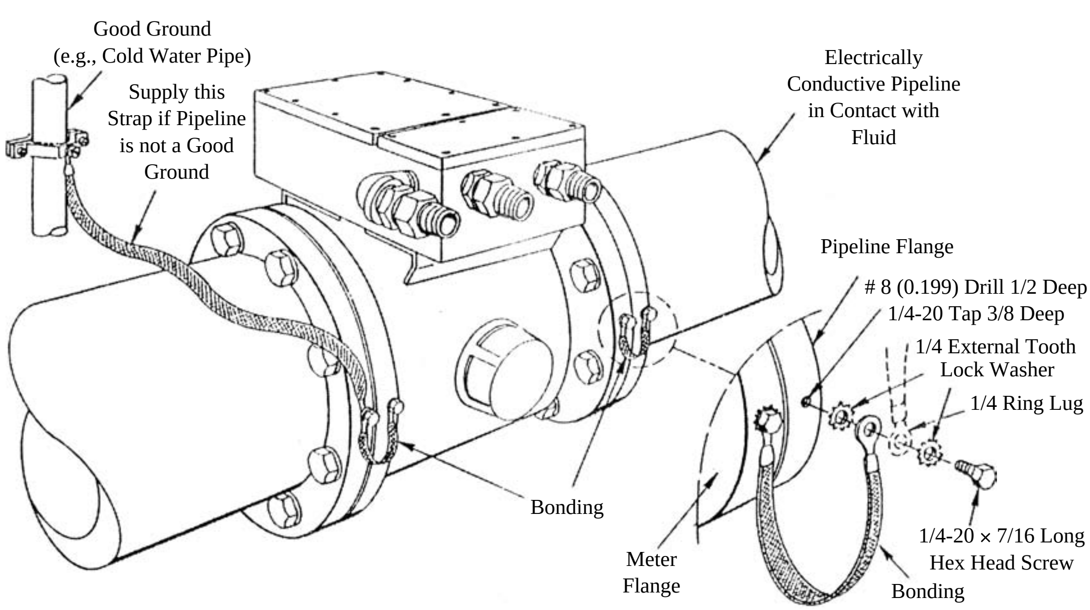


FIG. 2.10p
Typical bonding and grounding procedure. A good grounding is absolutely essential to isolate noise and high common mode potential. If the pipe is conductive and makes contact with the liquid the flowmeter should be grounded to the pipe. If the pipe is made from nonconductive materials, the ground rings should be installed to maintain contact with the process liquid. Improper grounding results in excessive common mode voltages that can severely limit the accuracy and damage the processing electronics.

The conservative installation of magnetic flowmeters requires 3 to 5 diameters of straight pipe, the same size as the flowmeter, to be installed upstream from the meter, plus 2 or 3 diameters downstream. Meters can be installed in horizontal pipelines, vertical pipelines, or sloping lines. It is essential to keep the electrodes in the horizontal plane to ensure uninterrupted contact with the liquid or slurry being metered. In gravity-feed systems, the meter must be kept continually full; therefore, the meter should be installed in a "low point" in horizontal lines or, preferably, in a vertical upflow line.

SIGNAL CONSIDERATIONS AND DEMODULATION TECHNIQUES

Each magnetic flowmeter requires electronics to convert the electrode output into a standardized analog or digital signal. The electronics can be mounted locally, directly on the flowmeter, or remotely. Integral mounting simplifies the installation, reduces cost, and eliminates the noise and other problems associated with the transmission of a low-level signal over a relatively long distance. The advantages of remote mounting include the reduced headroom requirement for the meter, accessibility, operator convenience, and the distancing of the sensitive electronics from the high-temperature or otherwise undesirable environment of the flowmeter. If shielded, twisted wires are used, the electronics can be 200 ft (67 m) from the meter.

The housings of the electronics can be designed for indoor or outdoor use and for general-purpose or hazardous environments. The converters can serve several flowmeters simultaneously and provide for interfacing with computers. The displays can provide flow rate or total flow indication. "Smart" magmeters provide the added features of self-diagnostic and detection of coil/converter/metering tube failure or of empty pipe, as well as switching, alarming, flow integration, and preset batching functions. They can also detect pipe blockage; signal erroneous settings; or change the range, engineering units, damping times (63% response time settable from 0.1 to 100 sec), or even the flow direction of metering.

Magnetic flowmeters are essentially four-wire devices that require an external power source for operations. Particularly in AC magnetic flowmeters, the high-voltage power cables and low-voltage signal cables must run separately, preferably in different conduits. In contrast, for DC magnetic flowmeters, the power and signal cables can be run in one conduit. This is because, in DC-type magnetic flowmeters, the voltage and the frequency of excitation of the electromagnets are much lower. Some manufacturers supply special cables along with their flowmeters.

Despite beliefs to the contrary, magnetic flowmeters demonstrate a certain degree of sensitivity to flow profiles. Another important aspect is the effect of turbulence. Unfortunately, there is very little information available on the behavior of turbulent flows when they are in transverse magnetic fields. Figure 2.10q shows an example of flow profile in which the velocity profile perturbed. The fluid is being retarded near the center of the channel and accelerated at the top and bottom near the electrodes.

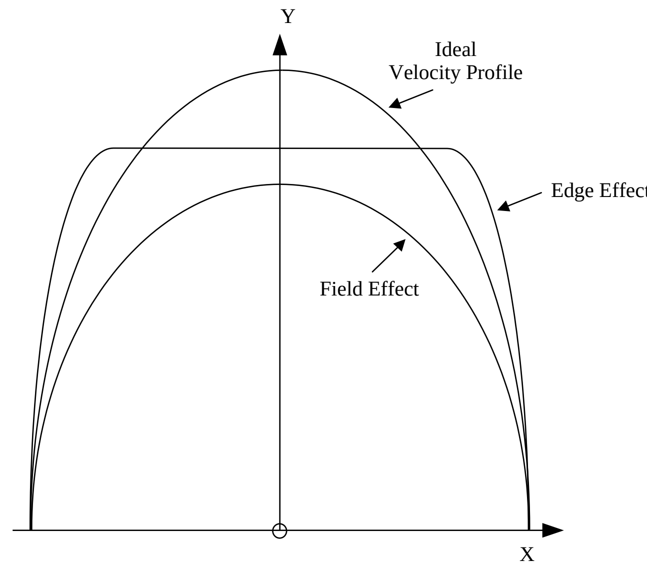


FIG. 2.10q
Flow profiles in the pipes. Magnetic flowmeters demonstrate a certain degree of sensitivity to flow profiles. The ideal velocity profile may be distorted due to edge effects and also field effects known as magneto-hydrodynamics. In some applications the velocity perturbation due to magneto-hydrodynamic effect may be serious enough to severely influence the accuracy of operations.

In AC flowmeters, the electrode signals may be amplified much more readily as compared with their DC counterparts. That is why AC flowmeters have been used successfully to measure very low flow rates as well as the flow of very weakly conducting fluids. Nevertheless, AC flowmeters tend to be more complicated, bulky, and expensive, and they require electromagnets with laminated yokes along with stabilized power supplies. In some magnetic flowmeters, it is feasible to obtain sufficiently large flow signal outputs without the use of yoke by means of producing magnetic fields by naked coils. In this case, the transformer action to the connecting leads may be reduced considerably.

One of the main drawbacks of AC-type flowmeters is that it is difficult to separate the signals caused by transformer action from the useful signals. The separation of the two signals is achieved by exploiting the fact that the flow-dependant signal and the transformer signal are in quadrature. That is, the useful signal is proportional to the field strength, and the transformer action is proportional to the time derivative of the field strength. The total voltage vT can be expressed as

$$v_T = v_F + v_t = V_F \sin(\omega t) + V_t \cos(\omega t) \qquad \textbf{2.10(7)}$$

where v_F is the induced voltage due to liquid flow, and v_t is the voltage due to transformer action on wires, and so on.

Phase-sensitive demodulation techniques can be employed to eliminate the transformer action voltage. The coil magnetizing current, $i_m = I_m \sin(\omega t)$ is sensed and multiplied with the total voltage v_T giving

$$v_T\, i_m = [V_F \sin(\omega t) + V_t \cos(\omega t)]\, I_m \sin(\omega t) \qquad \textbf{2.10(8)}$$

Integration of Equation 2.11(8) over one period between 0 and 2π eliminates the transformer voltage, yielding only the voltage that is proportional to the flow.

$$V_f = V_F I_m \pi \qquad \textbf{2.10(9)}$$

where V_f is the voltage after integration. This voltage is proportional to the induced voltage modified by constants I_m and π.

In reality, this situation can be much more complicated because of phase shift due to eddy currents in nearby solids and conductors. Other reasons for complexity may be the result of harmonics because of nonlinearities such as hysteresis, or caused by capacitive pickup.

Particularly in AC flowmeters, if the flowmeter is not grounded carefully relative to the potential of the fluid in the pipe, then the flowmeter electrodes may be exposed to excessive common-mode voltages that can severely limit the accuracy. In some cases, excessive ground potential can damage the electronics, because the least-resistance path to the ground for any stray voltage in the liquid would be via the electrodes.

Some commercial magnetic flowmeters have been developed that can operate on sawtooth or square waveforms. Standardized magnetic flowmeters and calibration data still do not exist, and manufacturers use their own particular design of flow channels, electromagnets, coils, and signal processors. Most manufacturers provide their own calibration data.

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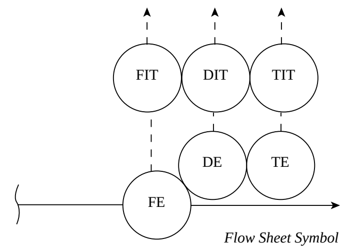
2.11 Mass Flowmeters, Coriolis

CATHY APPLE (1995) **MARTIN ANKLIN, WOLFGANG DRAHM** (2003)



Flow Sheet Symbol

Measured Variables	Mass flow, volume flow, density and temperature
Sizes	1/25 to 10 in. (1 to 250 mm)
Flow Range	0 to 63,000 lb/min (0 to 28,300 kg/min)
Fluids	Liquids, slurries, gases (compressed, low-pressure, etc.), liquefied gases; not gas-liquid mixtures
Output Signal	Linear frequency, analog, digital (HART, Profibus, FOUNDATION™ fieldbus, Modbus, scaled-pulse, display, alarm outputs, manufacturer-specified protocols)
Operating Pressure	Depends on tube size and flange rating: 1400 PSIG (100 bar) typical standard rating; 5000 PSIG (345 bars) typical high-pressure rating
Pressure Drop	Function of flow, viscosity, and design, varying from very low (<0.1 PSIG, 10 mbar) to moderately high (22 PSIG approximately 1.5 bar)
Operating Temperature	Depends on design: –60 to 400°F (–50 to 200°C) typical standard; 32 to 800°F (0 to 426°C) high-temperature, special versions also used for cryogenic applications
Materials of Construction	Stainless steel, Hastelloy®, titanium; special materials as tantalum, zirconium and others are available
Inaccuracy	±0.1% of rate ± (zero offset/mass flow rate) × 100% Zero offset depends on size and design of the flowmeter; for a 1-in. (25-mm) meter with a typical maximum flow rate of 650 lb/min (18,000 kg/h), the zero offset is typically 0.04 lb/min (0.9 kg/h), which is below 0.01% of the maximum flow value. Typical: 0.15% within the range of 10:1 of full-scale flow rate (FS) and 1% within the range of 100:1 of FS
Repeatability	Typical: 0.075% within the range of 10:1 of FS and 0.5% within the range of 100:1 of FS
Rangeability	Up to 100:1
Cost	Depends on size and design: 1/25 in. (1 mm), $5000; typical 1-in. (25-mm) meter, $7000; 6-in. (150-mm), $27,500
Partial List of Suppliers	ABB (www.abb.com) Bopp & Reuther (www.burhm.de) Danfoss A/S (www.danfoss.com)

Endress+Hauser Inc. (www.endress.com)
The Foxboro Co. (www.foxboro.com)
Krohne (www.krohne.com)
Micro Motion Inc. (www.emersonprocess.com)
Oval (www.oval.co.jp)
Rheonik (www.rheonik.de)
Schlumberger Industries (www.slb.com)
Smith Systems Inc. (www.smith-systems-inc.com)
Yokogawa (www.yokogawa.com)

In recent decades, there has been a great deal of interest in Coriolis mass flowmeters (CMFs). The market for CMFs grew dramatically in the late 1980s and the 1990s. Today, CMFs are widely accepted in many industrial fields, and their performance has improved steadily. One of the advantages of CMFs is that they measure the true mass flow directly, whereas other types measure only volumetric flow. The high accuracy and rangeability of CMFs is another reason for their fast growth and acceptance in industry. The commercially available units show a broad variety of designs, such as single-tube, dual-tube, bent-tube, and straight-tube. Since CMFs are available that incorporate different tube materials (e.g., stainless steel, Hastelloy®, titanium, zirconium, tantalum, and lined tubes), they can be used for all kinds of liquids or gases. CMFs are most common in the food and beverage, chemical and pharmaceutical, and, increasingly, oil and gas industries.

MEASURING PRINCIPLE AND THEORY

Principle

Coriolis mass flowmeters have the proven ability to record the total mass flow to better than 0.1% for water at moderate velocities. Each Coriolis instrument gets its own calibration factor that depends only on the geometrical data and material properties of the tube. Thus, the calibration factor is independent of fluid properties. The measuring principle of CMF is Coriolis force, which appears in rotating and oscillating (vibrating) systems. Such a vibrating system is shown in Figure 2.11a for a straight tube. The tube is excited by an external force $\vec{F}_E$. The excitation frequency is kept at the natural frequency of the tube, which minimizes the energy needed for vibration. The general expression for the Coriolis force is $\vec{F}_C = 2 \cdot m \cdot \vec{v} \times \vec{\omega}$, where $\vec{q} = m \cdot \vec{v}$ is mass flow and

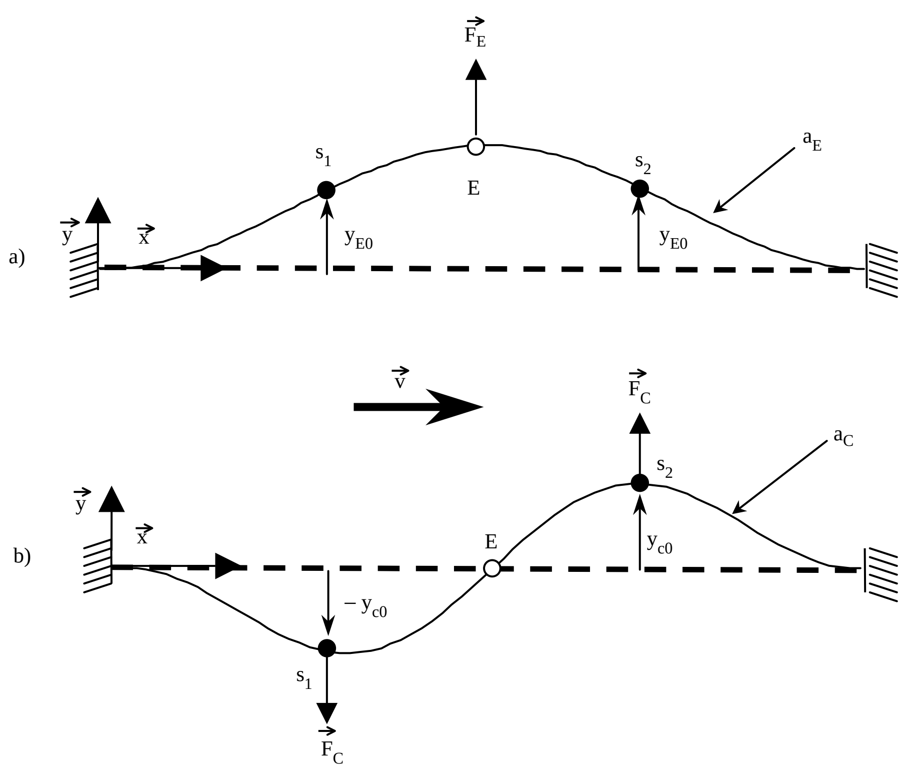


FIG. 2.11a
Panel a) describes the movement of a straight tube conveying a fluid, which is oscillating at the excitation frequency. The oscillation is maintained with the excitation force F_E at location E. The measuring signal is detected with the two sensors S_1 and S_2. When the fluid begins to flow, the Coriolis force F_C induces an oscillation as shown in panel b). The final lateral displacement is the superposition of both oscillations.

$\vec{\omega}$ is the rotation vector. When fluid is not flowing within a vibrating tube, the Coriolis force is zero ($\vec{F}_C = 0$). When fluid begins to flow, the Coriolis force is no longer zero ($\vec{F}_C \neq 0$), and the shape of the tube is illustrated by superimposing Figure 2.11a, panel (a) and panel (b). At the inlet section, the Coriolis force tends to decelerate the movement of the oscillating tube, whereas, for the outlet section, the Coriolis force tends to accelerate the movement. In the middle of the tube, the Coriolis force is always zero, since either $\vec{\omega}$ is zero for straight tubes or $\vec{q}$ is parallel with $\vec{\omega}$ for curved tubes, bringing the product $\vec{q} \times \vec{\omega}$ to zero. As soon as the fluid begins to flow, the Coriolis force induces a phase shift along the tube. This phase shift is proportional to the mass flow. The mass flow can then be determined by measuring the phase shift between two sensor positions, S_1 and S_2. Since the oscillation is kept at the natural frequency of the system, the frequency changes with changing density of the fluid in the tube; i.e., the natural frequency increases with decreasing density. Therefore, by knowing the actual frequency of the system, the density of the fluid can be calculated directly. Another direct measurement, in addition to mass flow and density, is the fluid temperature, which is measured by the CMF.

Theory

In the literature, there are different approaches to describe the dynamics of vibrating tube conveying a fluid or a gas (see, for example, Païdousses and Li[1] or Raszillier and Durst)[2]. The general problem is very complex, and an analytical solution 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 only through approximations or using finite element methods. In this section, we derive an analytical solution to determine mass flow in a simplified system. However, by solving this simple model, we gain insight into the major physical effects of CMF.

We consider a straight tube conveying a fluid. We first look at the first *eigenmode** of this system, which is shown in Figure 2.11a, panel (a). The tube is fixed at both ends, and the velocity $\vec{v}$ of the fluid shall be zero. The movement of the sensors S_1 and S_2 is described by the differential equation,

$$M_E \cdot \ddot{y}_E + K_E y_E = F_E \qquad \textbf{2.11(1)}$$

where

y_E = lateral excitation displacement at the sensor
F_E = excitation force
M_E = effective mass
K_E = the stiffness of the tube for the excitation mode
$\ddot{y} = \frac{d^2 y}{dt^2}$

We are looking for solutions with $y_E(t) = \hat{y}_E \sin(\omega t)$ and $F_E(t) = \hat{F}_E \cdot \sin(\omega t)$. The eigenfrequencies of this system are found by setting the excitation force $F_E(t)$ to zero. Inserting the trial function for $y_E(t)$ in Equation 2.11(1), we get the frequency of the first eigenmode,

$$\omega_E = \omega_E(\rho_{\text{Fluid}}) = \sqrt{\frac{K_E}{M_E}} \qquad \textbf{2.11(2)}$$

Aside from the tube properties, ω_E depends only on fluid density. Therefore, using Equation 2.11(2), the fluid density can directly be determined by measuring the frequency of the eigenmode. Now, we include the excitation force $F_E(t)$ to determine the lateral displacement at the sensors. Solving Equation 2.11(1) with trial functions $y_E(t)$ and $F_E(t)$ and Equation 2.11(2), we get

$$\hat{y}_E = \frac{\hat{F}_E}{K_E \cdot \left(1 - \frac{\omega^2}{\omega_E^2}\right)} \qquad \textbf{2.11(3)}$$

For commercially available instruments the amplitude for $\hat{y}_E$ varies between 10 μm and 1 mm, and the frequency, $f_E = \omega_E/2\pi$, typically ranges from 80 Hz to 1100 Hz. Equation 2.11(3) also shows that the excitation force $\hat{F}_E$ is at a minimum when the driving frequency, ω, is similar to the frequency of the eigenmode, ω_E. In a real system, damping will prevent the lateral movement from becoming infinite even if ω equals ω_E. When the fluid begins to flow, the second mode is induced by the Coriolis force as shown in Figure 2.11a, panel (b). For the Coriolis mode, the differential equation is

$$M_C \cdot \ddot{y}_C + K_C y_C = F_C \qquad \textbf{2.11(4)}$$

where y_C is the lateral Coriolis displacement of the tube at S_1 and S_2, F_C is the Coriolis force, M_C is the effective mass, and K_C represents the stiffness of the tube for the Coriolis mode. The trial function for the lateral displacement of the Coriolis mode is $y_C(t) = \hat{y}_C \cdot \cos(\omega t)$, and the function for the Coriolis force is $F_C(t) = \hat{F}_C \cdot \cos(\omega t)$. Using the same procedure as above, we get the frequency of the Coriolis mode $\omega_C = \sqrt{K_C/M_C}$, which is typically 2.7 times higher than ω_E. The lateral displacement at the sensors becomes

$$\hat{y}_C = \frac{\hat{F}_C}{K_C \cdot \left(1 - \frac{\omega_E^2}{\omega_C^2}\right)} \qquad \textbf{2.11(5)}$$

The Coriolis force F_C is calculated by integration along the tube

$$F_C = \int_0^{L/2} \dot{m} \cdot \dot{y}_E \cdot a_E'(x) \cdot a_C(x) \cdot dx$$
$$F_C = \dot{m} \cdot C_{EC} \cdot \dot{y}_E \qquad \textbf{2.11(6)}$$

* Resonance frequency or the first resonance frequency.

where C_{EC} is a coupling factor between the excitation and the Coriolis mode, $\dot{m}$ is the mass flow, L is the length of the tube, $a'_E = (da_E)/(dx)$ is the derivative of the normalized excitation mode shape, $\dot{y}_E \cdot a'$ is the local rotation velocity, and a_C is the normalized Coriolis mode shape shown in Figure 2.11a, panel (b). If we define $v_E = \dot{y}_E$ and with $\hat{v}_E = \hat{y}_E \cdot \omega$, we get $\dot{y}_E = \hat{y}_E \cdot \omega \cdot \cos(\omega t) = \hat{v}_E \cdot \cos(\omega t)$. Thus, Equation 2.11(6) becomes $\hat{F}_C = \dot{m} \cdot C_{EC} \cdot \hat{v}_E$, and the lateral displacement of the sensors, Equation 2.11(5), becomes

$$\hat{y}_C = \frac{\dot{m} \cdot C_{EC} \cdot \hat{v}_E}{K_C \cdot \left(1 - \frac{\omega_E^2}{\omega_C^2}\right)} \qquad \textbf{2.11(7)}$$

As described before, the final lateral displacement of S_1 and S_2 is the superposition of excitation mode and Coriolis mode. As seen in Figure 2.11a, the total lateral displacement of S_1 is $y_{S1} = y_E - y_C$, and for S_2 it is $y_{S2} = y_E + y_C$. The time difference $\Delta\tau$ between the two sensors becomes

$$\Delta\tau = \frac{\Delta\varphi}{\omega_E} \approx \frac{2 \cdot \hat{y}_C}{\omega_E \cdot \hat{y}_E} = \frac{2 \cdot \hat{y}_C}{\hat{v}_E} = \frac{2}{\omega_E} \cdot \frac{\overline{(y_{S2} - y_{S1})}}{(y_{S2} + y_{S1})} \qquad \textbf{2.11(8)}$$

where $\Delta\tau$ is the time lag and $\Delta\varphi$ is the phase shift between the two sensors. Now, we can determine the mass flow by inserting Equation 2.11(7) into 2.11(8), producing $\dot{m} = \frac{K_C \cdot (1 - \omega_E^2/\omega_C^2)}{2 \cdot C_{EC}} \cdot \Delta\tau$, where the expression $\frac{K_C \cdot (1 - \omega_E^2/\omega_C^2)}{2 \cdot C_{EC}}$ is a constant value C. Thus, by knowing $\Delta\tau$, the mass flow of a CMF can be determined through the simple equation

$$\dot{m} = C \cdot \Delta\tau \qquad \textbf{2.11(9)}$$

where the constant C does not depend on fluid properties. For commercially available CMFs, this constant is determined for each unit through calibration. Although we have derived the formula to determine the mass flow of this system, the model does not include effects such as axial pressure, in-line pressure, temperature, pulsation, compressibility, and so on. As mentioned before, analytical calculations including such effects are very cumbersome and can be achieved only as approximations. The experimentally found influences of these effects on mass flow measurements will be described below.

DESIGN OF CMF

Figure 2.11b shows the tube assembly of a CMF. Generally, it consists of two components: the flow tube assembly and the electronics. Typically, two electrodynamic pickups generate electrical signals containing the flow information. The signal processing unit implemented in the electronics calculates the flow from these signals, which are very small in amplitude. The flow is split into two tubes as shown in Figure 2.11b. Sensors are mounted at the inlet and outlet section of the tubes, measuring the phase difference between these two points. The tubes are forced into oscillation by the driver, which is mounted between the two tubes. Thus, the tubes are automatically driven in counterphase, which is the preferred type of motion. To vibrate the flow tubes, all commercially available CMFs use a magnet and a coil as the driving mechanism. Typically, the coil is mounted on one tube, and the magnet is mounted on the opposite tube. To protect the measuring system from any external disturbances, the tubes are fixed into a rigid carrier housing, which is strong

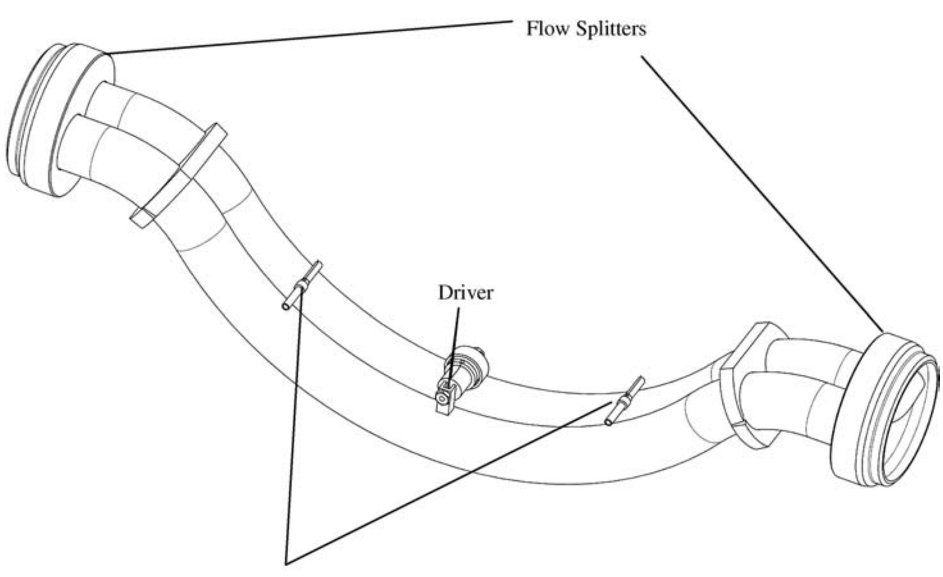


FIG. 2.11b
Tube assembly of a typical Coriolis flowmeter.

enough to isolate the system from the environment. This carrier housing is not shown in Figure 2.11b.

The tubes are vibrated at their natural frequency. As shown before, this frequency requires the least amount of energy to excite the system. Even large meters can be vibrated with only a few milliamps of excitation current. The natural frequency depends mainly on the mass of the system and the elastic properties of the measuring tubes. The total mass of the system includes the mass of the tube itself, the mass of the fluid within the tube, and the mass of any attached items such as driver and sensors. Therefore, since the material properties remain constant, a change in natural frequency directly indicates a change in the density of the fluid. As described before, this change in frequency can be used to determine the density of the fluid.

Balancing Systems for CMF

CMF are among the most accurate flowmeters on the market. This accuracy is achieved over a wide measuring range, which is required because, for example, liquids with high viscosities do not reach high velocities and have low total mass flow. A high turndown from maximum flow is also needed for gas flow measurements because, even at high pressure and at high velocity, the total mass flow rate for gas is small in comparison to mass flow rate of fluids. The accuracy for lower flow rates is limited by the zero-point errors. An error of 0.005% of full scale due to zero-point instability is typical.

In the previous section on "Theory," it is shown that mass flow induces very small displacements along the measuring tube. These displacements have to be measured accurately, even though the instruments are often mounted in a harsh process environment. A key parameter to achieve a precise and stable CMF reading is the decoupling of the internal measuring system from any environmental and external disturbances. If CMFs are not decoupled to near perfection, the oscillations from the measuring tube will be transmitted to the connected process piping, which in turn begins to vibrate as well. Vibrating process piping can then cause the CMF to be excited by undefined vibrations. Depending on the magnitude and the strength of such external excitations, this can lead to a disturbed reading of the CMF. Therefore, it is an important requirement of a CMF to be a balanced system, in which oscillations of the measuring tube are well defined within the meter and are not transmitted to flanges and process piping. This requirement is also a general rule to ensure a good zero-point stability.

Dual-Tube Meters

Designs with dual tubes offer the best performance for the decoupling of the measuring system from the process environment. Similar to a tuning fork, the two tubes vibrate in counterphase. While the oscillation is maintained, the forces at the fixation points of the two tubes are identical in absolute value but in counterphase directions. Ideally, this results in zero force acting on the flanges. The perfect symmetry of the two tubes is unaffected by changes in fluid density, temperature, pressure, viscosity, and so on.

The sensors shown in Figure 2.11b can be mounted between the two tubes and do not have to be supported by the housing. This results in maximum common-mode rejection and maximum suppression of externally induced vibrations. The mounting of the driver and sensors must be done in such a way that the overall mass balance of the tubes is maintained.

If the flow is not split completely symmetrically into the two measuring tubes, no additional error will occur, because the flow signal, which is due the Coriolis forces, is composed of the displacements of each tube separately and therefore is independent of the exact flow distribution. Thus, a well-defined flow profile is not a requirement for the design of a CMF. This also indicates that no special precautions are needed for installations near devices that may generate flow turbulences.

The majority of the commercially available CMFs use a double-tube design, because this offers the best performance with regard to accuracy and insensitivity to external disturbances. However, the dual-tube design requires flow splitters, which are not recommended for applications with fluids that are prone to plugging. Such fluids are often used in the food processing industry, where single-tube meters are required.

Single-Tube Meters

Generally, there are two different designs of single-tube flowmeters. In the first design, the tubes are bent to form a double loop. This design behaves similarly to the dual-tube flowmeter with the difference that the tubes are in series rather than parallel. Such single-tube flowmeters offer the same advantages as dual-tube meters, and they do not have the disadvantage of employing flow splitters. However, with this design, the tube length increases dramatically, which results in increased pressure loss. Furthermore, easy drainage of the instrument is impossible with this design. The second single-tube flowmeter design contains a straight, or fairly straight, single tube. From the customer's point of view, these designs are preferred, since they offer the best cleanability and the most prudent fluid handling. A challenge is to find a balancing mechanism for such flowmeters that allows accurate measurements for various process conditions and changing fluid densities. Nevertheless, straight (or fairly straight) single-tube CMFs are available that offer comparable performance to that of dual-tube flowmeters.

Tube Geometries

A variety of tube designs are currently available, a small selection of which is shown in Figure 2.11c. Most designs aim to magnify the effect of the Coriolis force by the geometrical form of the tubes. The larger the Coriolis effect

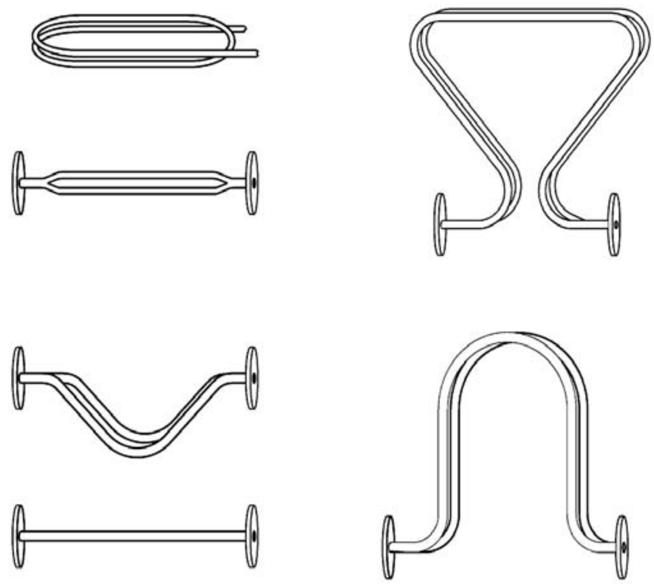


FIG. 2.11c
Selection of geometries of various Coriolis flowmeters.

becomes, the larger the time or phase difference between the flow sensors becomes, and the easier it is to determine the mass flow. Such magnifying geometrical forms often result in large tube loops that take up much space and have no advantage in zero-point stability, because external disturbances are also magnified. Thus, the signal-to-noise ratio remains the same. As electronics have become more and more efficient, the need for such geometrical magnification of the Coriolis effect has disappeared. Therefore, the large loops can be replaced by compact tube designs that require little space. An example of such a compact design is shown in Figure 2.11b. In addition, the compact design shortens the tube length, which results in higher oscillation frequencies of about 300 to 1100 Hz. Higher oscillation frequencies have the advantage of a better decoupling performance from pipeline vibrations and external disturbances, which are predominantly in the range of about 50 to 180 Hz.

For the dual-tube design, symmetry is the key factor, so a pair of tubes are chosen that are nearly identical in terms of mechanics. The two tubes have to be assembled in such a way that tube symmetry is not altered. Therefore, the production of these tube assemblies needs to be done very accurately, with a good understanding of the production process itself.

The main reason for using bent tubes is the thermal expansion of the measuring tube. While the fluid temperature may change by several hundred degrees Celsius, the temperature of the supporting structure changes much less, due to thermal transport, convection, and radiation. This can lead to large temperature differences between measuring tube and housing, which increase the axial forces of the tube. For a straight-tube CMF, the axial forces are largest and mainly depend on the expansion coefficient of the tube material. To prevent the tube from damage, the axial force must stay below a certain value, which depends on the material of the tube. By choosing a material with a low expansion coefficient, the axial forces can be kept below the critical value, even for straight tube CMF. Unfortunately, the rather high expansion coefficient of stainless steel, which is the most common material for measuring tubes, allows only a very restricted temperature range for a straight-tube design. Therefore, stainless steel tubes need to have a curved shape to reduce the maximum stress, since the tube can expand into the curve. All commercially available CMFs with straight tubes use titanium or zirconium for the measuring tubes, since these materials offer a small temperature expansion coefficient. With these materials, even great temperature differences between the measuring tube and the housing result in only small additional axial stress. Moreover, titanium offers higher stress limits than stainless steel. CMFs with single straight tubes are available for use up to 150°C.

With regard to corrosion, erosion, and pressure rating, the wall thickness of the measuring tubes should be as thick as possible. However, the sensitivity of the instrument to flow-induced Coriolis forces decreases with increasing wall thickness. Therefore, tube dimensions have to be optimized for several considerations, including the overall pressure loss. For a 1.5-in. (DN 40) dual-tube design, a typical size of the measuring tube is 1 in. (25 mm) inside diameter with a wall thickness of 1/16 in. (1.5 mm).

Flowmeters are commercially available with stainless steel, Hastelloy®, titanium, zirconium, and tantalum as tube material. Exotic materials such as glass or Tefzel®-lined tubes are also available for special purposes.

Sensors

As shown in Figure 2.11b, two motion sensors are needed to measure the displacement of the tube at the inlet and outlet sections. The phase difference or time lag between the two sensor signals is a measure of the mass flow. The sensor could be of any type that can represent the motion of the flow tubes, measuring position, velocity, or acceleration. At present, the most commonly used device is the electrodynamic sensor, in which a coil is mounted on one tube and a magnet on the other tube. The relative motion between the tubes induces a voltage in the coil, representing the differential velocity of the tubes. Electrodynamic sensors have the advantages of offering very good phase accuracy and high reliability.

Temperature Sensors

As described previously, mechanical properties change with temperature. This leads to axial stress and also changes the Young's modulus. An increase in temperature decreases the stiffness of the tube by lowering the Young's modulus. To compensate for the influence of thermal effects on CMF readings, each flowmeter needs to be equipped with at least one sensor to measure fluid temperature. 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 flowmeter for this effect. Instead of a second temperature sensor, the axial stress can also be detected by a strain gauge attached to the measuring tube.

Temperature sensors have uses beyond merely accounting for thermal effects. Because they measure the temperature of the fluid, temperature information is used as the third direct process signal of a CMF, in addition to mass flow and density.

Security

The oscillation amplitude of a CMF is very small (typically, 100 μm). Stress in the measuring tubes is limited to ensure reliable operation of the meter for many years and to protect the meter from damage due to tube oscillation.

The whole vibration system, including driver and sensors, is fixed in a solid housing, typically constructed of stainless steel. This housing can act as a secondary containment. The more compact the CMF, the smaller the housing can be and, possibly, the higher the pressure rating of the secondary containment. Housings with pressure ratings up to 1500 psi (100 bar) are available.

Because they employ a small excitation current, intrinsically safe CMF versions are available for use in hazardous areas. The electronics must be tested for electromagnetic compatibility (EMC), fulfilling general EMC requirements according to applicable guidelines.

Electronics

The drive circuit initiated the tube oscillation and maintains the oscillation at a certain amplitude. This circuit needs to be built to provide a fast response to changing fluid properties. Air bubbles, for example, cause a sudden increase in excitation power. This information has to be supplied to the driver quickly so as to keep the amplitude of the oscillation constant. The driver circuit also controls the excitation frequency.

The sensor signals are very small sinusoidal signals, which have to be amplified to make them processible in the succeeding signal processing stages of the electronics. These amplifiers need to have a very broad bandwidth to prevent the mass flow signal from containing additional zero-point errors.

The electronics can be mounted on the flowmeter directly, forming one compact flowmeter unit, or the flowmeter can be interfaced to the electronic via a cable. This permits the electronics to be located remotely from the sensor. The remote assembly may be necessary for high-temperature meters, or it may be convenient if the sensor is installed in a place that is not easily accessible.

Signal Processing

The sinusoidal signals from the two sensors are compared to determine either the time difference or phase shift between the two signals. The mass flow rate is calculated directly by multiplying the time difference or the phase shift with the calibration constant of the flowmeter. Furthermore, thermal effects on the mass flow and density reading have to be included as well. This is commonly done with a microprocessor. However, analog circuitry can also be used. Today, much analog circuitry is being replaced by digital signal processors, which offer powerful mathematical functions to allow, for example, filtering of the flow signals. With digital processing, the response time of a CMF becomes faster, and the reproducibility of the flow reading improves. Thus, with digital signal processors, CMFs become capable of controlling formidable applications such as rapid batching, where fast response and high accuracy are critical.

Communication/Output

The primary output from a CMF is mass flow. However, most electronic designs are also capable of providing temperature, density, and volumetric flow data. Furthermore, totalizers provide mass or volume totals.

Most electronics are equipped with configurable alarm outputs. Sophisticated relay functions are available whereby the CMF directly controls a valve in a batching process.

Many digital output protocols are supported (e.g., Profibus, FOUNDATION™ fieldbus, HART, Modbus, scaled pulse, and others), allowing a choice of communication solutions. However, current (4- to 20-mA) and frequency outputs for mass flow are still the preferred and most common output signal formats.

TECHNICAL DATA

Measuring Accuracy/Range

Figure 2.11d shows the excellent measuring accuracy and the large rangeability of CMF. During the 12-h test run, the zero point and the calibration factor remain stable and are well within the specification of the instrument. Note that the reading remains accurate even at low flow rates, even below 1/100 of the maximum flow rate specified for the CMF.

Pressure Drop

The pressure drop depends on tube design and mainly depends on the length of the tube and its inner diameter. For the pressure drop of CMF with dual tubes, the design of the flow splitter is also important. The lowest pressure drop occurs with single straight-tube flowmeters, where the inner diameter of the measuring tube is identical to that of the connected process pipe. Typical pressure drops at the maximum flow speeds specified by manufacturers are 7 to 20 PSIG (0.5 to 1.5 bar) referred to water. For the measurements shown in Figure 2.11d, the pressure drop at 80 in./sec (2 m/s) is only 0.4 PSIG (30 mbar).

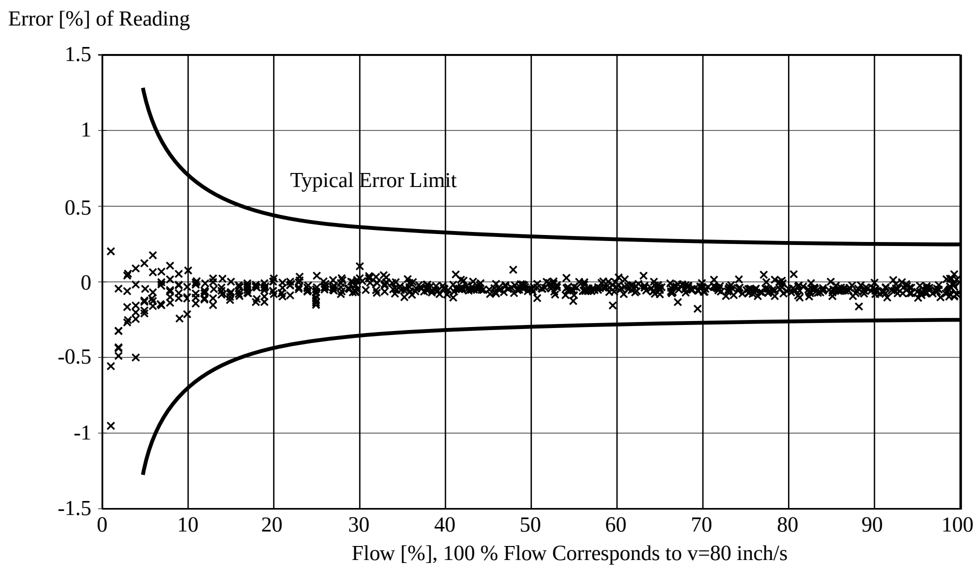


FIG. 2.11d
This figure shows the measuring uncertainty for a 1" (DN25) Coriolis flowmeter. The maximum flow speed is 80 in./s (2 m/s), which is 20% of the maximum specified flow speed of the flowmeter. The curves show the specified error limits.

Influences on the CMF Reading

While improving the accuracy of CMFs during the past decade, many effects, mostly secondary, can be identified that influence the performance of a CMF. These effects can be roughly separated into two groups.

1. Effects such as changing fluid temperature, for which CMF can directly account
2. Effects like external vibration, for which CMF cannot directly account

The latter effects are minimized by either the design layout or, if that is not possible, by special installation or correction instructions. In this section, we will briefly describe different effects.

Temperature As mentioned previously, changing fluid and housing temperatures will affect the elastic properties of the CMF and thus influence the mass flow and density readings. We can account for this effect directly by measuring the fluid and housing temperatures separately. On the other hand, temperature changes can also influence the zero offset and the performance of the electronic components to some degree. The drift in electronic components will usually lead to changes in the zero offset of the flowmeter. Both influences can be minimized by using a special design that does not require any further corrections or installation instructions.

In-Line Pressure With changing in-line pressure, the tube becomes slightly deformed, which influences the stiffness of the layout and thus can affect the reading of the CMF. With special designs, this effect can be minimized.

Mounting Pipe stress is introduced not only by in-line pressure and temperature, as described before, but also by different mounting conditions. These conditions may cause compression, tension, or shear forces to be applied to the flowmeter, which may affect the zero offset of the CMF. The influence of these effects has been greatly reduced during the last decade so that, today, a zero-point calibration is needed only for special applications as described below.

Vibration In most applications CMFs are exposed to some external vibrations. Such vibrations can occur as a result of the pumping system or nearby vibrating devices, or they may be flow induced as observed in pipeline systems. External vibrations typically occur at 50 to 180 Hz. As mentioned previously, CMFs are designed such that the effect of external influences is minimized. Therefore, external vibration plays a minor role and generally has no effect on the accuracy of the CMF reading. However, if the external vibration is close to the working frequency of the CMF, measurement errors will occur. It has been shown that pulsation is critical not only at the working frequency (f_E) of the CMF but also at frequencies $f = f_C - f_E$, where f_C is the Coriolis frequency.[3] Therefore, CMFs with high working frequencies are much less sensitive to pulsation and external vibrations than others. This is because both f_E and the difference $f_C - f_E$ are high; i.e., above roughly 200 Hz. For severely vibrating applications, where the low working frequency of the CMF might become critical, the influence of the external vibration can be greatly reduced by using flexible piping and vibration-isolating pipe supports.

Humidity Because CMFs are typically enclosed in sealed cases that are completely isolated from atmospheric conditions, external humidity has only a minor influence. Also, the flowmeter electronics are commonly enclosed in a housing that provides protection against external humidity. However, in CMFs with inadequate case seals or damaged housings, extremely humid environments can create condensation on the flow detector coils, which may lead to corrosion and component failure.

Fluid Velocity It is well known that the velocity of the fluid can slightly influence the accuracy of the CMF reading.[1] This is a minor effect, which is below the specified accuracy of most CMFs and does not necessarily require any correction. Nevertheless, given that the velocity of the fluid is known, a CMF can directly account for this effect.

Gas Measurements Only in recent years has it been shown that the compressibility of gas can affect the accuracy of the CMF reading.[4] Although this effect can be neglected for most fluids, it becomes relevant for gases in which the speed of sound is diminished. Knowledge about this effect allows us to correct the reading of CMF.

Two-Component Flow A CMF may be suitable for homogeneous two-phase (solid/liquid) flows and for heterogeneous flows. Such applications include many food processes, sand in water, pulverized coal in nitrogen, water in oil, and many others. To measure two-phase fluids, single-tube meters may be preferable.

Corrosion, Erosion Corrosion and erosion diminish the wall thickness and therefore change the stiffness of the tube, which can lead to faulty CMF readings. Since CMFs are available with different tube materials, corrosion can significantly be reduced by choosing the appropriate material for each application. To reduce erosion caused by highly abrasive media, it is necessary to keep the flow velocity low. Erosion also depends on the design of CMF and is smallest in straight, single tubes.

Reynolds Number Although the accuracy of a CMF generally does not depend on the flow profile, the sensitivity changes slightly from laminar flow to eddy flow. Knowledge of the Reynolds number allows us to determine the state of the flow regime and thus to account for it directly.

Installation

Some general recommendations for installations are applicable to all CMFs. The measuring tubes should remain full of the process fluid. Mixtures of gas and liquid should be avoided. For gas measurements, the tubes should be filled with gas only, with no fluid droplets present.

The preferred installation orientation is vertical, with an upward flow direction. With this orientation, entrained solids can sink downward, and gases can escape upward, when the medium is not flowing. This also allows the measuring tubes to be completely drained and protects them from solid build up.

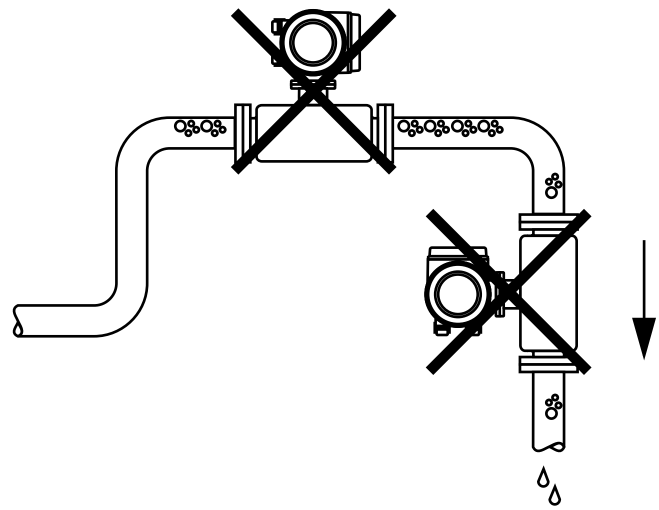


FIG. 2.11e
Not recommended mounting location of a CMF.

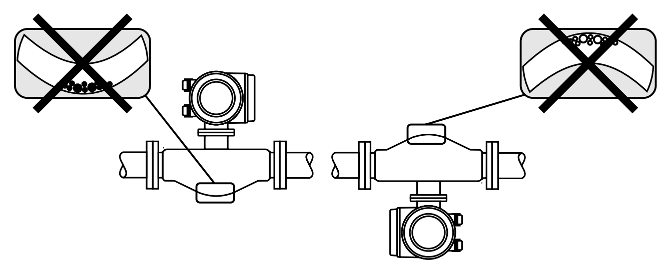


FIG. 2.11f
Orientation of CMF with curved tubes; the orientation shown in the left panel is not suitable for fluids with solids content; the orientation shown in the right panel is not suitable for outgassing fluids.

When measuring liquids, the CMF should not be installed at the highest point of the system, because gas may accumulate in the flowmeter as shown in Figure 2.11e. Installation in a vertical pipeline directly upstream of a free pipe outlet should also be avoided.

With curved tubes, the CMF orientation should be adapted to type of fluid used. Figure 2.11f illustrates problems with outgassing fluids and with fluids containing solid particles.

Mechanical Installation Modern CMFs offer good balance in the vibration system and therefore have no specific installation requirements. The CMF can be installed easily in a pipeline. When heavy CMFs are used, mechanical support of the pipeline has to be considered. Pipeline supports should not be attached directly to the sensor, and the CMF should not be used to support process piping directly.

TABLE 2.11g
Examples of Common Coriolis Flowmeter Applications

Food and Beverage	*Chemical and Petrochemical*		*Petroleum Products*
Beer, soda	Adhesives	Hydrogen peroxide	Asphalt
Chocolate	Alcohol	Latex	Bunker C
Fruit juice	Ammonia	Nitric acid	Crude oil
Honey	Catalysts	Phosgene	Diesel fuel
Ice cream	Caustic	Phosphoric acid	Fuel oil
Margarine	Cyclohexane	Polyol	Gasoline
Milk	Ethylene	Propylene	Hydraulic oil
Molasses	Formaldehyde	Resins	Jet fuel
Peanut butter	Freon®	Solvents	Kerosene
Pet food	Glycerine	Styrene	Lube oil blending
Tomato paste	Glycol	Sulfuric acid	Oil/water emulsion
Animal, vegetable fat	Hydrochloric acid	Toluene	Tar
Pharmaceutical	*Pulp and Paper*	*Other*	
Alcohols	Antifoaming agents	Compressed gases: nitrogen, helium, carbon dioxide, CNG	
IV bag filling	Black liquor	Dyes	
Palm oil	Cellulose slurry	Ink	
Perfume	Paper pulp	Liquefied gases: carbon dioxide, LPG, LNG	
Pill coatings	Red liquor	Magnetic tape coating	
Soap	Titanium dioxide	Paint	
Sodium methylate		Photographic emulsion	
Talcum powder		Wax	
Vitamins		Filling airbags (automobile industry)	

Zero-Point Adjustment (Static/Dynamic) After factory calibration of a CMF, the calibration factor and the zero point are stored in the electronics. CMFs that have good balance, and thus are decoupled from connected piping, are not affected by the installation into the process piping. As a result, the zero point will not change, and no special zero-point adjustment is necessary. Practical experience has shown that a zero-point calibration is required only in special cases; for example, to achieve the highest measuring accuracy possible in the presence of very slow flow rates or in the case of extreme process conditions such as very high fluid temperatures.

Zero-point calibration is carried out using completely filled measuring tubes with no mass flow. During the zero-point adjustment, care has to be taken that no gas or solids are present in the measuring tube. Keeping the in-line pressure high during the zero-point calibration reduces the risk of gas formation in the CMF and thus increases the accuracy of the zero-point calibration.

FIG. 2.11h
This picture illustrates a CMF installed into a compact space. The shown CMF is a single-tube Promass I. (Courtesy of Endress+Hauser Flowtec AG.)

APPLICATIONS

CMFs are currently used in many areas, including chemical, petroleum, petrochemical, pharmaceutical, food and beverage, and pulp and paper industries. Because of their versatility, CMFs are used for process control, batching, inventory, precision filling of containers, custody transfer, and other applications. An overview of some of them is presented in Table 2.11g. CMFs are suitable for many applications, because they can be very compact and do not have any upstream or downstream piping restrictions. An example of a compact application is shown in Figure 2.11h. The photo shows a single-tube CMF Promass I from Endress+Hauser Flowtec AG. Note that inlet and outlet parts are bent at a 90° angle and that the available room is very limited.

ADVANTAGES OF CMFs

1. One of most important advantages of CMFs is that mass flow is measured directly. This can be performed with high accuracy, typically with 0.1% error. High accuracy is also maintained over wide ranges of temperatures (typically from –50 to +200°C) and in-line pressures. Furthermore, CMFs are extremely linear over their entire flow range.
2. CMF rangeability is extremely high. Measurements can still be performed at low flow rates, 100 times lower than the maximum flow rate specified.
3. In addition to direct measurement of mass flow, temperature and density are measured directly. Knowledge about density allows us to convert mass flow data into volume flow data.
4. The measuring principle is independent of the flow profile of the fluid or gas. Therefore, no flow conditioner or special upstream or downstream pieces are required. A CMF can also be used with a pulsating flow.
5. The accuracy of a CMF is independent of fluid properties such as viscosity or density. Therefore, a CMF can measure all kinds of fluids, including Newtonian and non-Newtonian fluids, slurries, and gases.
6. CMFs do not have any moving parts that wear out and require replacement. This reduces the need for and the cost of maintenance.
7. Single-tube CMFs do not have internal obstructions that could be damaged or plugged.
8. CMFs are designed to measure forward and reverse flows with high accuracy.
9. Because CMFs are available based on different construction materials, they can be used for many different applications, including corrosive fluids.
10. The design of CMFs allow them to operate with low power requirements.

LIMITATIONS OF CMFs

1. CMF prices are rather high as compared to other measuring device types. However, to measure mass flow with a volumetric meter, it is often necessary to install an in-line densitometer, which brings the cost up to roughly the equivalent of a CMF alone.
2. There are no CMFs available for medium temperatures above 800°F (426°C).
3. CMFs cannot be used for liquids with any significant gas content. This effect can be reduced by increasing the in-line pressure.
4. CMFs are not available for large pipelines; the largest CMF has a maximum flow rate of 63,000 lb/min (28,300 kg/min) using flanges with 10-in. (25-cm) diameters. To measure higher flow rates, two or more CMFs must be mounted in parallel.
5. CMFs are not suitable for gas applications with low in-line pressure, since low-pressure gases have low densities. To generate enough mass flow to provide a sufficient Coriolis signal, the velocity of the gas must be quite high. This may lead to a large pressure drop across the meter.

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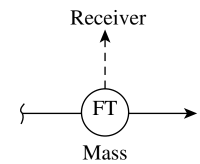
2.12 Mass Flowmeters—Miscellaneous



Flow Sheet Symbol

R. SIEV (1969) **K. O. PLACHE** (1982) **B. G. LIPTÁK** (1995)
J. E. JAMISON (2003)

Types	A. Flow computers using inputs from volumetric flow sensors and densitometers, or pressure/temperature transmitters B. Doppler ultrasonic or magnetic flowmeter and radiation-type densitometer combinations C. Angular momentum and other similar principles D. Linear hydraulic Wheatstone-type
Applications	Gas, liquid, solids
Design Pressures and Temperatures	Magmeter/radiation units available up to 255 PSIG (17.5 bars) and 300°F (150°C)
Pipe Sizes Available	A. Unlimited B. 2 to 36 in. (50 mm to 0.9 m) C. Small diameters only—aero turbine fuel applications D. Under 1 in. (25 mm), for very low flows only
Errors (Inaccuracy)	Varies with the designs, generally approximately ±1% of full scale
Costs	A. Flow computers without the sensors can cost approximately \$600 minimum; \$700 to \$4000 normally, depending on options, features, remote communications capabilities, and so on B. A 6-in. (150-mm) magmeter/radiation combination costs about \$13,000 C. Costs vary substantially with size and materials of construction D. Price starts at about \$2000 minimum; normally \$7000 to \$13,000, depending on model, options, and range required
Partial List of Suppliers	Barton Instrument Systems Ltd. (www.barton-canada.com) (A) Bristol Babcock (www.bristolbabcock.com) (A) Contrec Inc. (www.contrec.com.au) (A) ELDEC Corp., a Crane Company (www.eldec.com) (C) Kessler-Ellis Products (KEP) Co. (www.kep.com) (A) Omega Engineering Inc. (www.omega.com) (A) Pierburg Instruments Inc. (www.pierburginstruments.com) (D) Pierburg GMBH (www.pierburg-instruments.de) (D) Solartron Mobrey (www.solartronusa.com) (A) Thermo MeasureTech (www.thermomt.com) (B) Universal Flow Monitors Inc. (www.flowmeters.com) (A) West Coast Research Corp. (www.members.aol.com/wescores) (A) Yokogawa Corp. of America (www.yca.com) (A)

A knowledge of mass flow rates is necessary in combustion fuel control, reactor recipe formulations, and many other applications, including the mining and dredging, food, pulp and paper, pharmaceuticals, and chemical industries. The various weighing systems, solids flowmeters, and the more frequently used liquid/gas mass flowmeters (such as Coriolis and thermal types) are discussed in Sections 2.11 and 2.13. In this section, some of the other mass flow detection methods are covered.

RADIATION-TYPE MASS FLOWMETERS

One of the earliest methods of mass flow determination was to install two separate sensors—one to measure the volumetric flow and the other to detect the density of the flowing stream—and then to use the two transmitter signals as inputs into a mass flow computing module. This approach was feasible, but it required coordination between the products of different suppliers and corrections for such process variables as temperature, pressure, viscosity, particle size, and velocity profile changes. The introduction of density/mass flow systems has made it easier to use this technique. The key working component in these combinational designs is the multiple-input transmitter (Figure 2.12a), which, in addition to a radiation-type density input, accepts a flow measurement signal from any volumetric flowmeter. Based on these two inputs, the microprocessor-based transmitter generates an output signal that relates to mass flow.

A further improvement occurred in the design of these density/mass flow systems in which the density and volumetric flow sensors were combined in a single package (Figure 2.12b). These units are composed of a either a Doppler ultrasonic flowmeter or a magnetic flowmeter and a gamma-radiation-based densitometer, all in a single unit including a microcomputer. These mass flow units do not require compensation for changes in process variables and are installed as a single, obstructionless mass flow sensor. Its features and materials of construction are similar to those of a magnetic or ultrasonic flowmeter except that it is bulkier and more expensive because it incorporates a radiation-type densitometer. If the flow sensor is a magnetic flowmeter, the unit is also limited to use on process fluids having at least 3.0 μS/cm conductivity.

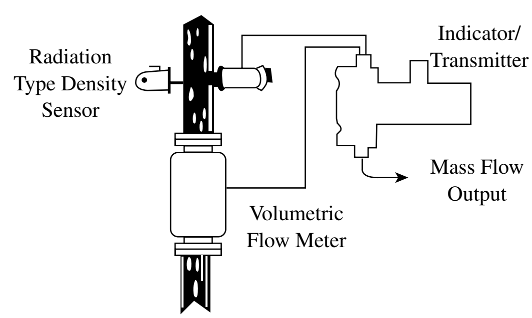


FIG. 2.12a
Combination mass flow system.

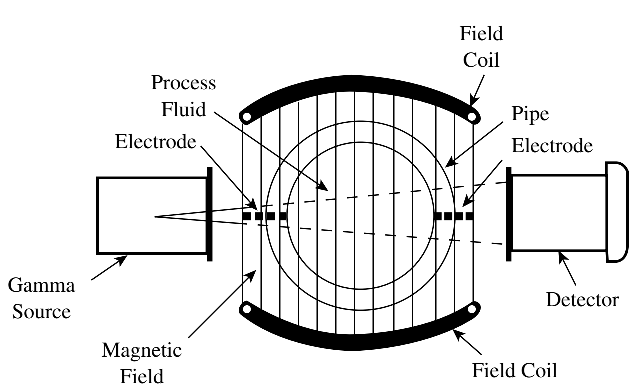


FIG. 2.12b
Mass flowmeter combining a magnetic flowmeter and a radiation-type densitometer in a single unit.

ANGULAR MOMENTUM-TYPE MASS FLOWMETERS

The principle of angular momentum can best be described by referring to Newton's second law of angular motion and the definition of angular momentum, using the following notation:

H = angular momentum (lbf-ft-sec)
I = moment of inertia (lbf-ft^2)
ω = angular velocity (rad/sec)
α = angular acceleration (rad/sec^2)
Y = torque (ft-lbf)
r = radius of gyration (ft)
m = mass (slugs)
t = time (sec)

Newton's second law of angular motion states that

$$Y = I\alpha \qquad \textbf{2.12(1)}$$

and defines that

$$H = I\omega \qquad \textbf{2.12(2)}$$

But because, by definition,

$$I = mr^2 \qquad \textbf{2.12(3)}$$

Equation 2.12(1) becomes

$$Y = mr^2\alpha \qquad \textbf{2.12(4)}$$

and Equation 2.12(2) becomes

$$H = mr^2\omega \qquad \textbf{2.12(5)}$$

Because

$$\alpha = \frac{\omega}{t} \qquad \textbf{2.12(6)}$$

Equation 2.12(4) becomes

$$Y = \frac{m}{t} r^2\omega \qquad \textbf{2.12(7)}$$

Solving for mass flow rate, $\frac{m}{t}$, (lbm/sec), we get

$$\frac{m}{t} = \frac{Y}{r^2\omega} \tag{2.12(8)}$$

Also, dividing both sides of Equation 2.12(5) by t,

$$\frac{H}{t} = \frac{m}{t} r^2\omega \tag{2.12(9)}$$

Because torque is expressed in terms of force, the right-hand side of Equation 2.12(8) must be multiplied by g (32.2 ft/sec^2 or 9.8 m/sec^2) to obtain a dimensionally correct equation. Therefore, since r^2 is a constant for any given system, the mass flow of fluid can be determined if an angular momentum is introduced into the fluid stream and measurements are made of the torque produced by this angular momentum and of the fluid's angular velocity.

Impeller-Turbine Flowmeter

The impeller-turbine-type mass flowmeter uses two rotating elements in the fluid stream, an impeller and a turbine (see Figure 2.12c). Both elements contain channels through which the fluid flows. The impeller is driven at a constant speed by a synchronous motor through a magnetic coupling and imparts an angular velocity to the fluid as it flows through the meter. The turbine located downstream of the impeller removes all angular momentum from the fluid and thus receives a torque proportional to the angular momentum. This turbine is restrained by a spring that deflects through an angle that is proportional to the torque exerted upon it by the fluid, thus giving a measure of mass flow.

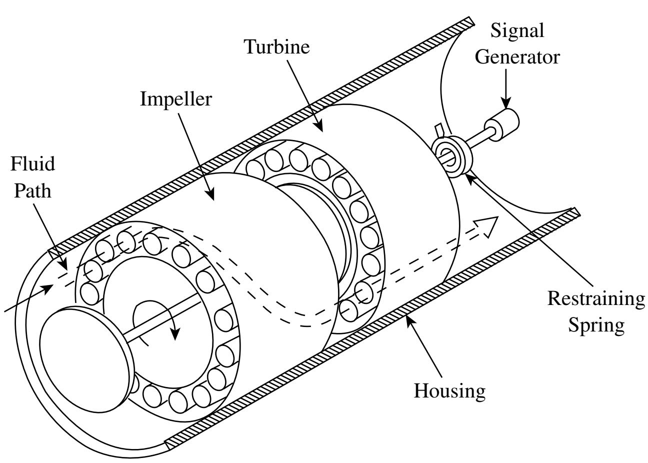


FIG. 2.12c
Impeller-turbine mass flowmeter. (Illustration reproduced by permission of the General Electric Co.)

Constant Torque-Hysteresis Clutch

Another angular-momentum type mass flowmeter eliminates the necessity of making a torque measurement after imparting a constant torque to the fluid stream. The relationship between mass flow and torque is

$$\frac{m}{t} = \frac{Y}{r^2\omega} \tag{2.12(10)}$$

Therefore, if Y is held at a constant value, and since r^2 is a physical constant of any given system,

$$\frac{m}{t} = \frac{k}{\omega} \tag{2.12(11)}$$

This relationship is used in designing a mass flowmeter as follows:

1. A synchronous motor is placed in the center of the flowmeter assembly.
2. This motor is magnetically coupled to an impeller that is located within the flowing process stream.
3. The magnetic coupling between the motor and the impeller is provided by means of a hysteresis clutch that transmits a constant torque from the motor to the impeller.

Thus, a measurement of the rotational speed of the impeller is inversely proportional to the mass flow rate.

Twin-Turbine Flowmeter

Another angular-momentum-type device is the twin-turbine mass flowmeter. New developments in this technology are also discussed in Section 2.25, which covers turbine flowmeters.

In this instrument, two turbines are mounted on a common shaft (see Figure 2.12d). They are connected with a calibrated torsion member. A reluctance-type pickup coil is

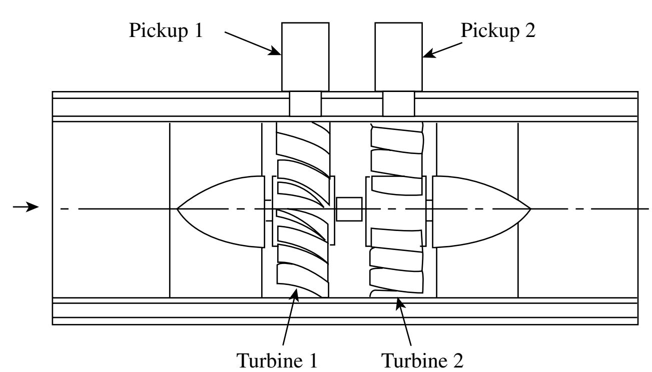


FIG. 2.12d
Twin-turbine mass flowmeter.

mounted over each turbine, and a strong magnet is located in each turbine within the twin-turbine assembly.

Each turbine is designed with a different blade angle; therefore, there is a tendency for the turbines to turn at different angular velocities. However, because the motion of the turbines is restricted by the coupling torsion member, the entire assembly rotates in unison at some average velocity, and an angular phase shift is developed between the two turbines. This angle is a direct function of the angular momentum of the fluid. As previously shown, angular momentum can be measured by torque, and angular momentum is a function of mass flow. In the twin-turbine assembly, the turbines are not restrained by a spring, but the torsion member that holds them together is twisted. This torsion member has a well established torsion-spring rate (ft-lbf/rad). Therefore, the angle developed between the two turbines is a direct function of the twist or torque exerted by the system.

This angle is measured by a unique method. As each turbine magnet passes its own pickup coil, the coil generates a pulse. The pulse from the upstream turbine is used to open a so-called electronic gate, while the pulse from the downstream turbine closes this gate. An oscillator is placed in the electronic circuit, and the oscillations are counted while the gate is opened. The number of oscillations is thus a function of the angle between the two turbines. Knowledge of the angle gives the value of torque, which, in turn, is proportional to mass flow rate.

Coriolis

Coriolis mass flowmeters are discussed in detail in Section 2.11 and are mentioned here only for the purpose of completeness. The classic Coriolis-type mass flowmeter (see Figure 2.12e) consists of a centrifugal-pump impeller wheel and a vaned sensing wheel that acts as a turbine wheel to extract the angular momentum imparted to the fluid by the impeller. The sensing (or turbine) wheel is contained in the same housing as the impeller and is attached to the latter by a strain gauge; the combination is driven at a known constant speed. The power applied to the impeller is merely that required to overcome the frictional drag of the system.

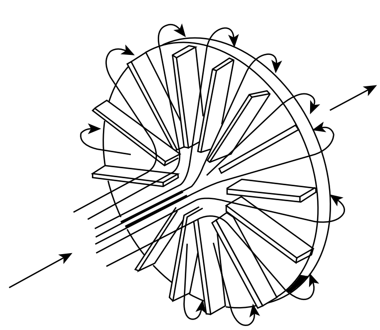


FIG. 2.12e
Classical Coriolis mass flowmeter.

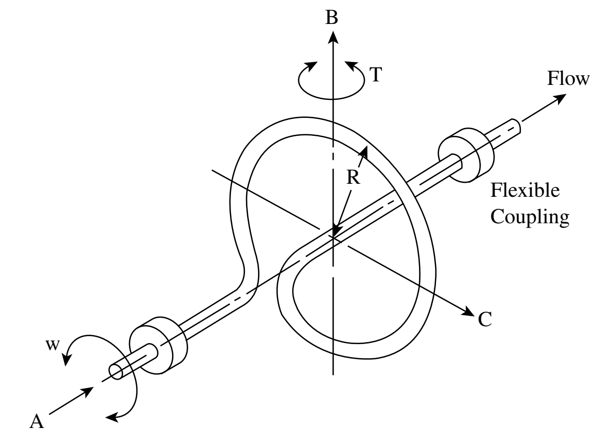


FIG. 2.12f
Gyroscopic mass flowmeter.

The torque measured is that required to impart to the fluid stream a Coriolis acceleration, given by the expression

$$Y = \omega\left(R_2^2 - R_1^2\right)\frac{m}{t} \qquad \textbf{2.12(12)}$$

where R_2 and R_1 = outer and inner radii (ft).

Comprehensive analysis and laboratory testing of this type of flowmeter are described in Reference 1.

Gyroscopic

Another angular momentum mass flowmeter (Figure 2.12f) operates on the principle of a gyroscope. It consists of a pipe shaped in the form of a circle or a square. A motor introduces an oscillating vibration at a constant angular velocity ω about the A axis. When the fluid passes through the loop, a precession-type moment is produced about the B axis and is measured by the deflection of a sensing element. This deflection can be shown to be directly proportional to mass flow.

The gyroscopic mass flowmeter can handle slurries in the medium pressure and temperature ranges, but its industrial use is very limited as a result of its high cost and inability to handle high flow rates. The gyroscopic and basic Coriolis flowmeters described earlier were generally not successful in the mass-flow-measurement market. A newer combination of the two principles has resulted in the highly successful Coriolis mass flowmeter described in the previous section.

LINEAR MASS FLOWMETERS

The linear mass flowmeter is, in principle, a hydraulic equivalent of the electrical Wheatstone bridge. Four matched orifices make up the bridge, and an integral constant flow recirculating pump establishes the internal reference flow. Sensing imbalance generated by external flow through the meter, the hydraulic bridge produces an output of differential pressure that is both linear and proportional to the true mass liquid flow.

This flowmeter has a wide rangeability and is unaffected by changes in process temperature, density, and viscosity. It is a fast-responding flowmeter that can detect very low flows at very low pressure drops. This meter is widely used in the automotive industry and wherever engines and fuel systems are checked, such as in the manufacturing of fuel injectors.

INDIRECT MASS FLOWMETERS

As is shown in Figure 2.12a, mass flow can also be obtained as the product of volumetric flow and density. In the case of measuring the mass flow of steam, one can also measure its volumetric flow and multiply it by density, which is obtained indirectly from the measurements of steam pressure and temperature. This technique is commonly used in the monitoring of steam distribution and determining steam losses caused by leakage, poor insulation, and so on.

Calculating the Mass Flow of Steam

Water at atmospheric pressure boils at 212°F. The boiling temperature of water is affected by pressure and, as the pressure drops, the boiling point decreases; as it rises, the boiling point increases. This pressure-temperature relationship is as follows:

Pressure	*Boiling Point, °F (°C)*
14.696 psia	212 (100)
50 psia	281 (138)
100 psia	328 (164)
200 psia	382 (194)
400 psia	445 (229)
800 psia	518 (270)

The boiling temperature of water at any given pressure is called the *saturation temperature,* and the steam produced at these temperatures is referred to as s*aturated steam*. If the steam temperature is increased over the saturation temperature, it is referred to as *superheated steam,* and the temperature difference between the saturation and the actual temperature is referred to as *degrees of superheat.* So, for example, if 100 psia steam is at 428°F, it has 100° of superheat.

Steam Density and Accounting

If the steam temperature and pressure are known, the internal energy, which is called *enthalpy*, is also known, as provided by the steam tables in the appendix of this handbook. From the steam tables, it is seen that the density of steam is also a function of only its temperature and pressure. Therefore, by measuring the temperature and pressure of steam, its density can be calculated, and if the volumetric flow of the steam is known, its mass flow can be calculated as the product of the two.

TABLE 2.12g
Plant Steam Balances

Boiler Output	*Volumetric Plant Consumption*	*Mass Plant Consumption*
20,000 lb/h (67,340 ft^3/h)	Weaving: 13,841 ft^3/h	4000 lb/h
	Spinning: 14,286 ft^3/h	4000 lb/h
	Finishing: 14,706 ft^3/h	4000 lb/h
	Services: 30,534 ft^3/h	8000 lb/h
Total: 20,000 lb/h (67,340 ft^3/h)	Total: 77,367 ft^3/h	Total: 20,000 lb/h

The energy content of steam is a function of its enthalpy. When steam is purchased for heating or to drive turbines, it is usually paid for on the basis of enthalpy. Therefore, by measuring the pressure, temperature, and volumetric flow of steam, one can calculate the mass flow or heat flow of steam.

The heat content of the steam drops, and some of the steam is also lost, as it travels from the boiler to the various users. This is the result of

- Insufficient thermal insulation of pipes
- Leaking joints on valves, pipes and other equipment
- Long line lengths

Example*

The steam distribution example given in Table 2.12g and Figure 2.12h is that of a textile factory. From Table 2.12g, one can observe that, when measured by volumetric flowmeters only (which disregard the effects of the drop in steam pressure as it travels through the distribution pipe lines), the total steam consumption appeared to be 9% greater than the volumetric flow of the steam as it left the boiler. On the other hand, if the measurements at the individual users are corrected for the drops in the pressure and temperatures at the users (and if no steam loss occurs due to leakage or condensation), this error can be eliminated through mass flow calculation.

Such calculations have the additional advantage of being able to provide the plant operator with information not only on mass flow but also on heat flow or total consumption of both mass and heat. In addition, such monitoring packages can keep records of pressure, temperature, specific volume, and enthalpy variations.

CONCLUSION

The most successful mass flowmeters have been described in the previous section (Section 2.11), but the devices covered in this section also have their applications. For example, the integrated ultrasonic or magnetic flowmeter/radiation densitometer package is the best solution for mass flow measurement of large slurry streams, in size ranges of 12 in.

* This is an example of an application of computer-type mass flowmeters, used with permission of Kessler-Ellis Products.

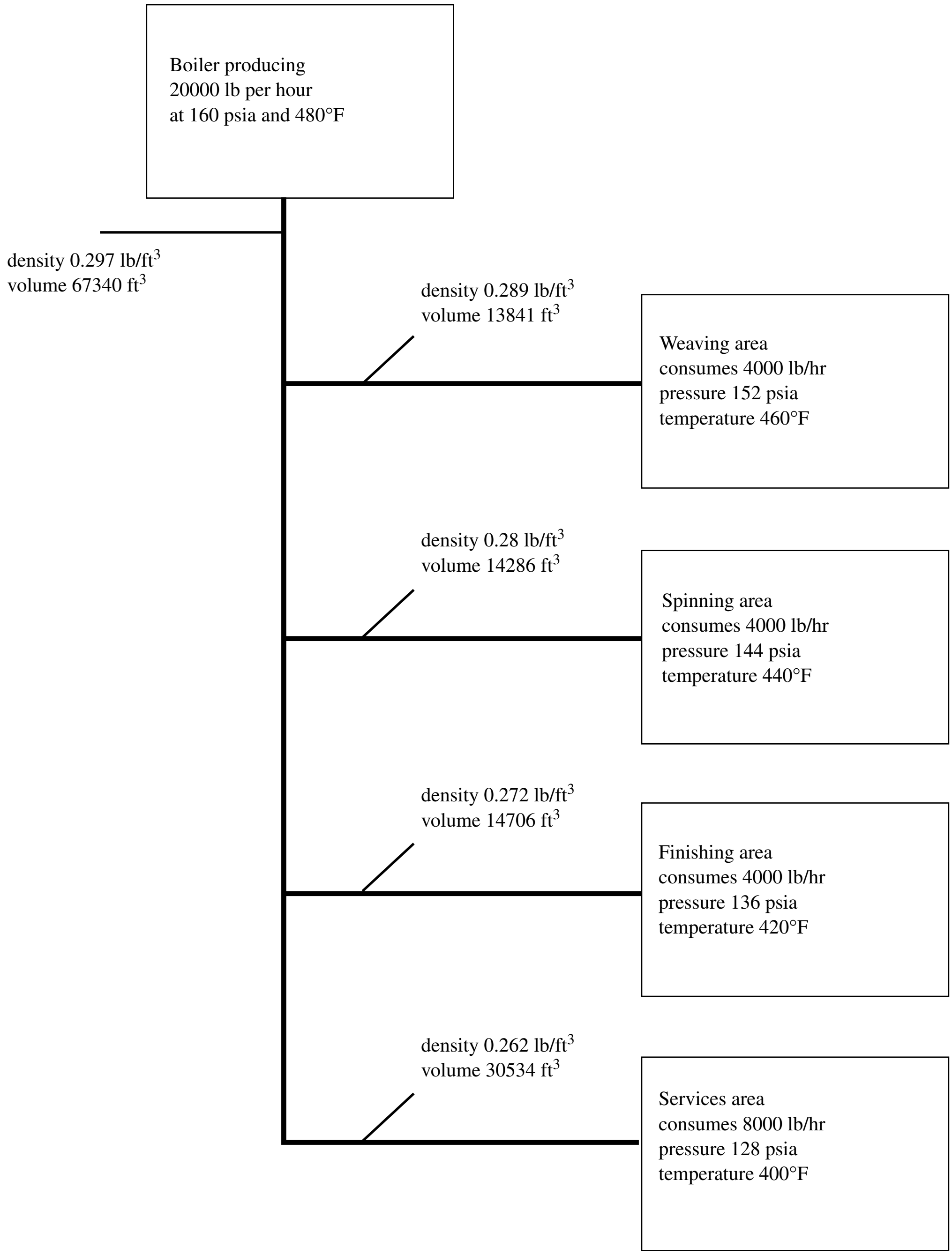


FIG. 2.12h
Plant steam balance example.

(300 mm) and above. Also, the flow computer approach sees many practical applications in many industries.

Accurate mass flow detection frequently can increase the efficiency of processes or allow for optimization, which results in energy or fuel conservation in combustion systems.

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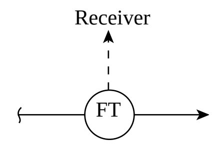
2.13 Mass Flowmeters—Thermal

R. SIEV (1969, 1982) **B. G. LIPTÁK** (1995) **T. J. BAAN** (2003)



Thermal
Flow Sheet Symbol

Types	A. Heat transfer-type mass flowmeters B. Thermal mass flowmeters employing externally heated capillary bypass sensor tubes and main conduits with laminar flow elements C. Heated-element-type mass flowmeters (note: Thermal flow switches are discussed in Section 2.7)
Check Cross Design Temperature	A. Up to 350°F (176°C), higher with special designs B. Some limited to 105°F (40°C) operation; others up to 300°F (150°C) C. Standard units up to 140°F (60°C), special ones up to 930°F (500°C)
Design Pressure	A. Up to 1200 PSIG (83 bars), higher with special designs B. Up to 1000 PSIG (69 bars) C. Low-pressure designs up to 15 PSIG (1 bar); others up to 1000 PSIG (69 bars) in smaller sizes
Pressure Drop	A. Usually, only a few inches of water B. Up to 45 PSIG (3 bars) C. Same as A
Process Fluids	A. Air, gas, liquids, and slurries B. Gases, some very low flow rate liquid devices C. Gases and liquids
Flow Range	A. From 0.5 sccm to 40,000 lbm/h (10,000 kg/h) B. Flow control units from 0 to 10 sccm to 0 to 35 scfm (0 to 1000 slm); special units up to 0 to 500 scfm (0 to 14 scmm) C. From 0 to 50 sccm to 0 to 2500 scfm (0 to 70 scmm)
Error (Inaccuracy)	±1% to ±2% of full scale, some better
Rangeability	10:1 to 100:1
Materials of Construction	Stainless steel, glass, Teflon™, Monel®, and so on
Cost	A type "B" thermal mass-flowmeter costs $500 and up, mass flow controller for low gas flows costs about $700 and up; purged probes for stack velocity measurement cost about $4500 each
Partial List of Suppliers	Aalborg Instruments & Controls Inc. (www.aalborg.com) (gas) Advance-Tech Controls Pvt. Ltd. (www.advancetechindia.com) (gas) Air Monitor Corp. (www.airmonitor.com) (air) Analyt-MTC GmbH (www.analyt-mtc.de) (gas) Brooks Instrument Div. of Emerson (www.emersonprocess.com) (gas, liquid) Cole-Parmer Instrument Co. (www.coleparmer.com) (gas, liquid) Eldridge Products Inc. (www.epiflow.com) (gas) E-T-A Control Instruments (www.etacbe.com) (flow switch) Extech Equipment Pty. Ltd. (www.extech.com.au) (gas) FCI Fluid Components, Inc. (www.fluidcomponents.com) (gas, liquid)

Flow and Level Controls (flow switch)
Hydril Co. (www.hydril.com) (flow switch)
Integrated Control Concepts Inc. (www.icci-inc.com) (gas)
Intek Inc., Rheotherm Div. (www.intekflow.com) (gas, liquid)
Kinetics/Unit Instruments (www.kineticsgroup.com) (gas)
Kurz Instruments Inc. (www.kurzinstruments.com) (gas)
Matheson Tri-Gas (www.matheson-trigas.com) (gas)
MKS Instruments Inc. (www.mksinst.com) (gas)
M-tek (www.vacuumresearch.com) (liquid)
Mykrolis Corporation (www.mykrolis.com) (gas)
Porter Instrument Co. (www.porterinstrument.com) (gas)
Scott Specialty Gases Inc. (www.scottgas.com) (gas)
Sierra Instruments Inc. (www.sierrainstruments.com) (gas)
Teledyne Hastings Instruments (www.hastings-inst.com) (gas)
Thermal Instrument Co. (www.thermalinstrument.com) (gas, liquid, slurry)
TSI Inc. (www.tsi.com) (gas, liquid)

Thermal flowmeters can be divided into the following two categories:

1. Flowmeters that measure the rise in temperature of the fluid after a known amount of heat has been added to it. They can be called *heat transfer flowmeters*.
2. Flowmeters that measure the effect of the flowing fluid on a hot body. These instruments are sometimes called *hot-wire probes* or *heated-thermopile flowmeters*.

Both types of flowmeters can be used to measure flow rates in terms of mass, which is a very desirable measurement, especially on gas service.

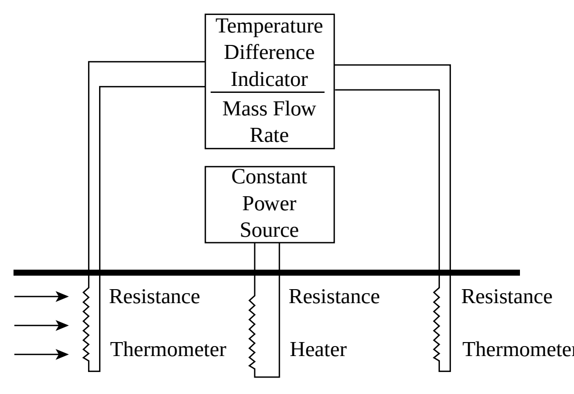


FIG. 2.13a
Heat transfer flowmeter.

HEAT TRANSFER FLOWMETERS

The operation of the heat transfer flowmeter is based on

$$Q = Wc_p(T_2 - T_1) \qquad \textbf{2.13(1)}$$

where

Q = heat transferred (BTU/h or Cal/h)
W = mass flow rate of fluid (lbm/h or kgm/h)
c_p = specific heat of fluid (BTU/lbm °F or cal/kgm °C)
T_1 = temperature of the fluid before heat is transferred to it (°F or °C)
T_2 = temperature of the fluid after heat has been transferred to it (°F or °C)

Solving for W, we get

$$W = \frac{Q}{C_p(T_2 - T_1)} \qquad \textbf{2.13(2)}$$

A simple flowmeter based on this equation is shown schematically in Figure 2.13a. Heat is added to the fluid stream with an electric immersion heater. The power to the heater equals the heat transferred to the fluid (Q) and is measured using a wattmeter. T_1 and T_2 are thermocouples or resistance thermometers. Since we know the fluid, we also know the value of its specific heat. Thus, by measuring Q, T_1, and T_2, the flow rate (W) can be calculated. T_1 and T_2 do not have to be separately detected; they can be connected to each other so that the temperature difference ($T_1 - T_2$) is measured directly.

A flowmeter of this type of construction has many limitations. The temperature sensors and the heater must protrude into the fluid stream. Thus, these components (particularly the heater) are easily damaged by corrosion and erosion. Furthermore, the integrity of the piping is sacrificed by the protrusions into the fluid stream, increasing the danger of leakage.

To overcome these problems, the heater and the upstream and downstream temperature sensors can be mounted outside of the piping (see Figure 2.13b). In this type of construction, the heat transfer mechanism becomes more complicated, and the relationship between mass flow and temperature difference becomes nonlinear. Figure 2.13c illustrates this nonlinear shift in ΔT in a heated-tube-type flowmeter, where the asymmetricity of the temperature distribution increases with flow.

To understand the operating principle of this flowmeter, we must review the effects of fluid mechanics and heat transfer. When a fluid flows in a pipe (turbulent or laminar), a thin

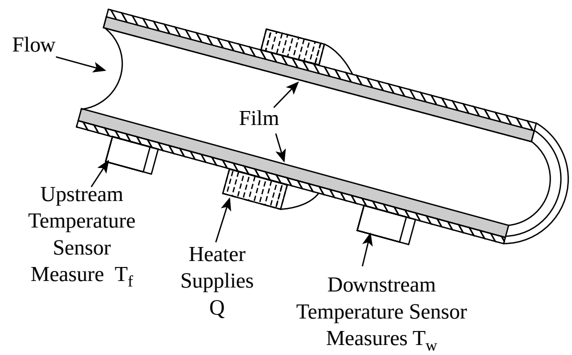


FIG. 2.13b
Thermal flowmeter with external elements and heater.

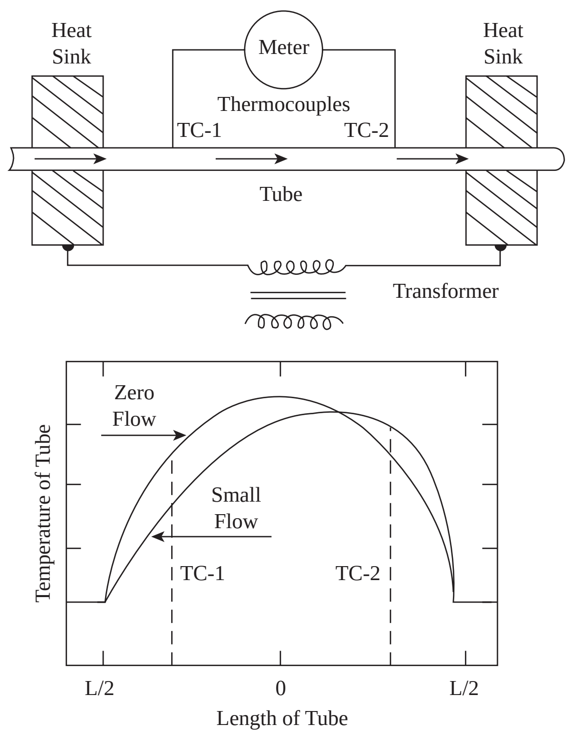


FIG. 2.13c
Heated-tube-type mass flowmeter.

layer (film) exists between the main body of the fluid and the pipe wall. When heat is passing through the pipe wall to the fluid, this layer resists the flow of heat. If the heater is sufficiently insulated, and if the piping material is a good heat conductor, the heat transfer from the heater to the fluid can be expressed as

$$Q = hA(T_{\text{wall}} - T_{\text{fluid}}) \qquad \textbf{2.13(3)}$$

where

h = film heat transfer coefficient [BTU/(hr × ft^2 × °F)]
A = area of pipe through which heat is passing (ft^2)
T_{wall} = temperature of wall (°F)
T_{fluid} = temperature of fluid (°F)

The film heat transfer coefficient, *h*, can be defined in terms of fluid properties and tube dimensions for both laminar and turbulent flow.[1]

$$h_{\text{turbulent}} = \frac{0.023K^{0.6}c_p^{0.4}W^{0.8}}{D^{1.8}\mu_1^{0.4}} \qquad \textbf{2.13(4)}$$

$$h_{\text{turbulent}} = \frac{1.75K^{0.67}c_p^{0.33}W^{0.33}}{DL^{0.33}} \qquad \textbf{2.13(5)}$$

where

K = thermal conductivity of the fluid [BTU/(hr × ft × °F)]
c_p = specific heat of the fluid [BTU/(lbm × °F)]
D = pipe diameter (ft)
L = heated length (ft)
μ_1 = absolute viscosity of the fluid (lbf/h-ft^2)
W = flow rate (lbm/h)

Using the turbulent flow condition as an example, and solving Equations 2.13(3) for *h* and 2.13(4) for *W*,

$$h = \frac{Q}{A(T_{\text{wall}} - T_{\text{fluid}})} \qquad \textbf{2.13(6)}$$

$$W^{0.8} = \frac{hD^{1.8}\mu_1^{0.4}}{0.023K^{0.6}c_p^{0.4}} \qquad \textbf{2.13(7)}$$

Substituting Equation 2.13(6) into 2.13(7),

$$W^{0.8} = \frac{QD^{1.8}\mu_1^{0.4}}{0.024K^{0.6}c_p^{0.4}A(T_{\text{wall}} - T_{\text{fluid}})} \qquad \textbf{2.13(8)}$$

Therefore, the mass flow (*W*) will vary with $T_{\text{wall}} - T_{\text{fluid}}$ if the fluid properties (μ, *K*, and c_p) and the meter design parameters (*Q*, *D*, and *A*) are all held constant. Letting all these constants = *X*,

$$W^{0.8} = \frac{X}{T_{\text{wall}} - T_{\text{fluid}}} \qquad \textbf{2.13(9)}$$

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. Thus, flow rate is obtained by measuring ΔT if the geometry of the flowmeter, the thermal conductivity, the thermal capacity and viscosity of the fluid, and the heater power are constant. This type of flowmeter can also be operated by keeping the ΔT constant and measuring the required power to the heater.

When building and/or using a flowmeter based on heat transfer principles, an instrument engineer must tread with caution. One must be sure that the values that have been assumed to be constants are truly so. One must also understand that relationships such as those given in Equations 2.13(4) and 2.13(5) are limited to a range of Reynolds numbers, L/D ratios, and so on. Finally, it is highly recommended that this type of instrument be calibrated, either by the manufacturer or by the user, under conditions that as nearly as possible duplicate its actual application.

These types of flowmeters are best suited for the measurement of homogeneous gases and are not recommended for applications in which the process fluid composition or moisture content is variable. For these flowmeters to be useful in a system, both the thermal conductivity and the specific heat of the process fluid must be constant.

Bypass-Type Designs

To facilitate measurement and control of larger flow rates, heat transfer-type flowmeters with bypass designs have been introduced (Figure 2.13d). Bypass thermal mass flowmeters are comprised of a capillary sensor tube connected to the main flow conduit as a shunt line. Sensor tubes with wall thicknesses as low as 0.002 in. (0.051 mm), usually with inside diameters of under 0.125 in. (3 mm), are fitted with three precision windings externally. The one in the middle is used to transfer heat through the thin wall to the fluid stream inside; the other two are upstream and downstream of the heater, serving to monitor temperature differences. The temperature gradient is due to fluid flow carrying heat from upstream to downstream in the sensor tube.

Measurements are taken by Wheatstone bridge configurations. The main flow conduit includes a laminar flow element to ensure laminar flow and also to act as a restriction forcing a portion of the flow into the sensor tube. Two conduits, if connected in a bypass pattern maintaining laminar flow, will sustain a constant ratio of their flow rates. When zero-flow conditions exist, the temperature differential between upstream and downstream sections is zero. Under flow conditions, fluids carry heat from upstream toward downstream sections of the sensor tube, and the change in resistance is directly proportional to the temperature, and thus, to the mass molecular flow of the gas medium. As the flow through the sensor tube is a function of the temperature gradient, the mass flowmeter can be calibrated to express the total rate of flow in suitable engineering units.

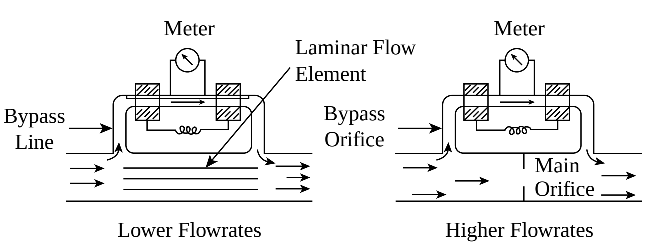


FIG. 2.13d
Bypass-type thermal mass flowmeters.

The smaller the diameter of the sensor tube, the faster the response, although, at the same time, the danger of impediment-related failure increases. There are two kinds of sensor tubes: straight and U-shaped. The advantage of U-shaped tubes is the more compact "footprint" of the mass flowmeter and controller, whereas straight tube designs facilitate stress-free conditions and the possibility of cleaning of the sensor tubes. Shunting sensor tubes ensure laminar flow over the full operating range of the meter. Additionally, small size is advantageous in minimizing the electric power requirement and also in increasing their speed of response, but it requires the use of upstream filters to protect against obstructions. Some units require up to 45 PSIG (3 bars) pressure drop to develop laminar flow conditions.

Traditional analog thermal mass flowmeters and controllers are increasingly being replaced by digital devices with advanced capabilities including user-accessible programming, totalizing, multiple primary calibrations, built-in correction factor libraries, RS-485 interface to permit up to 256 thermal mass flow devices to be controlled from a single PC, and other features. Communication protocols are available in HART, Profibus, and other configurations.

Mass flow controllers consist of flow measurement modules and automatic control valves assembled into compact closed-loop devices (Figure 2.13e). The cost of these units is very competitive. Therefore, if it is sufficient to control the flow of small gas streams to within ±1% of full scale, these units represent a good selection. Flow is most frequently controlled by variable-stroke electromagnetic valves. Thermal expansion valves are also available. Such valves are operated without seals and therefore without friction or wear.

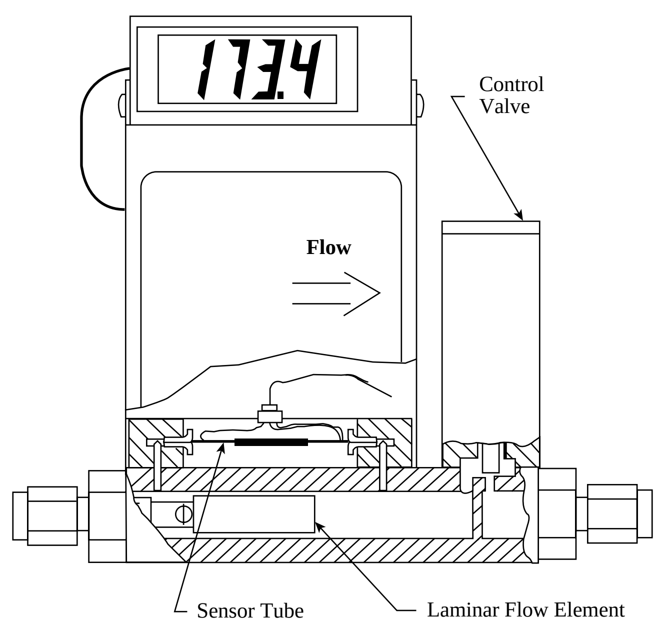


FIG. 2.13e
Bypass-type thermal mass flow controller with readout. (Courtesy AALBORG Instruments & Controls Inc.)

The stem of a thermal expansion valve is heated by the controller, and the expanding stem moves the valve plug into the seat, thereby closing the valve. Due to the type of valve actuator used, it takes 5 to 30 sec to bring the flow to setpoint. Mass flow controllers with flow capacities above 100 sL/min use linear step motor actuated mechanical valves. Proportionating electromagnetic valves have the fastest response, typically facilitating 800 ms time constants, or bringing setpoint-controlled flow rates to within ±2% of full-scale values over 20 to 100% of flow range within 2 sec. Linear step motor valves will typically reach set point values of ±2% of FS within 5 sec over the entire flow range of the meter.

Process applications should be evaluated from the point of view of fast time constants, which sometimes may be accompanied by undesirable overshoot and undershoot attributes vs. slower operations with "soft landings." This is a crucial factor in semiconductor manufacturing processes, where an overshoot condition may destroy a whole batch of expensive silicon wafers.

HOT-WIRE PROBES

In this design, two thermocouples (A and B) are connected in series to form a thermopile. A schematic of this type of flowmeter is shown in Figure 2.13f. This thermopile is heated by passing an alternating current through it. A third thermocouple (C) is placed in the direct current output circuit of the thermopile. Alternating current does not pass through this thermocouple, and it is therefore not electrically heated. This assembly is inserted into the process fluid (usually gas) stream. The gas cools the heated thermopile by convection. Because the AC input power to the thermopile is held constant, the thermopile will attain an equilibrium temperature and produce an emf that is a function of the gas temperature, velocity, density, specific heat, and thermal conductivity. The third, unheated thermocouple (C) generates an emf that is proportional to the gas temperature. This cancels the effect of the ambient gas temperature on the output signal of the heated thermopile. A and B are the heated thermocouples; C is the unheated one.

The output signal (voltage) of this instrument is given by the equation derived by King.[2]

$$e = \frac{C}{2(\pi K c_p \rho d v)^{1/2} + K} \qquad \textbf{2.13(10)}$$

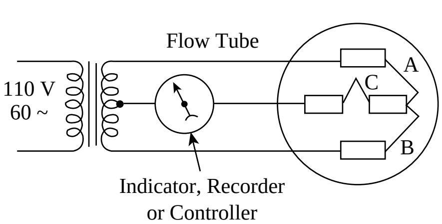


FIG. 2.13f
Hot wire flow-sensing probe.

where
e = voltage generated
C = instrument constant
K = thermal conductivity of fluid (BTU/h-ft-°F)
c_p = specific heat of fluid (BTU/lbm-°F)
d = diameter of heated thermocouple wire (ft)
v = velocity of fluid (ft/h)
ρ = density of the fluid (lbm/ft^3)

Once the instrument has been calibrated for a certain gas, a change in the gas temperature will have little effect on the gas properties and thus on the output signal. For example, the properties of air, over a wide range of temperatures, are as follows:

Temp. (°F)	*K (BTU/h-ft-°F)*	*c_p (BTU/lbm°F)*	*ρ (lbm/ft^3)*	*$(Kc_p\rho)^{1/2}$*
70	0.0150	0.243	0.0753	0.0165
500	0.0246	0.245	0.0416	0.0159
1000	0.0359	0.263	0.0274	0.0161

Because K (in the denominator) is very small, and because the term $(Kc_p\rho)^{1/2}$ remains constant over a wide range of temperatures, this type of instrument can be used to measure the mass flow rate of gases.

The hot-wire-type sensors are also used as air velocity sensors. These devices are called *anemometers*. A major limitation of the hot-wire-type mass flowmeters is similar to the limitations of all pitot-type flowmeters, namely that they do not detect the mass flow across the full cross section of the pipe—only at the sensor. Therefore, if the sensor is installed in a nonrepresentative location across the velocity profile, the resulting reading will be in error. The more recent developments in the design of this type of flowmeter include a more rugged mass flow sensor element, an integral (usually 10-diameter-long) pipe section to ensure smooth velocity profiles, and a conditioning nozzle that eliminates boundary layer effects and concentrates the flow onto the sensor (Figure 2.13g). These sensors can also be provided with

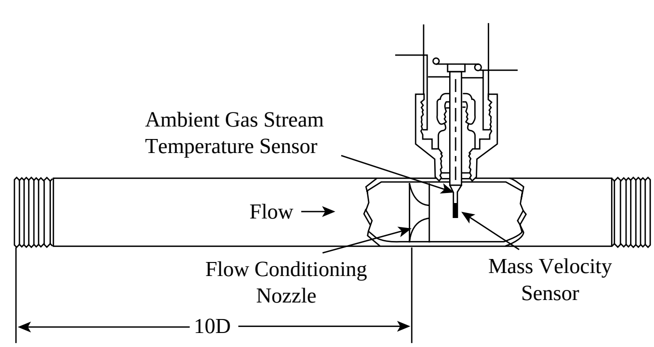


FIG. 2.13g
Complete mass flow sensor assembly. (Courtesy Kurz Instruments Inc.)

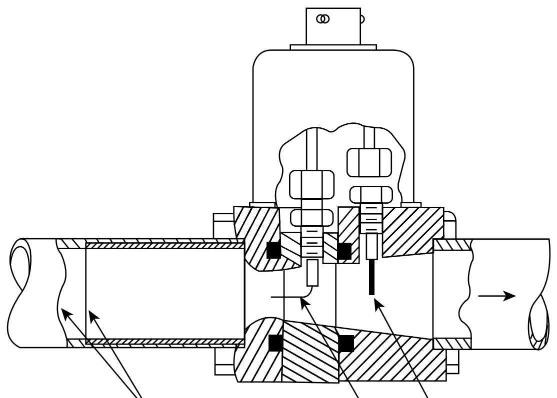


FIG. 2.13h
Venturi-type thermal mass flowmeter. (Courtesy TSI Inc.)

controllers and control valves to result in a complete flow control loop.

Other designs place the heated mass flow sensor at the throat of a venturi and add a screen upstream to make the flow profile more uniform (Figure 2.13h). These units are offered for both liquid and gas service. Other designs are of the insertion-probe type. Their flow ranges are a function only of the size of the pipe into which they are inserted, whereas their performance is similarly influenced by the correctness of the insertion depth (as are all pitot tubes).

CALIBRATING THERMAL MASS FLOW DEVICES

(See also Chapter 1, Section 1.4, "System Accuracy," and Section 1.8, "Instrument Calibration.")

Gas Flowmeter Calibrations

Gas calibrations are generally performed at standard conditions (STP) of $P = 101325$ Pa and $T = 20°$. Calibrating small gas flow rates of up to 20 slpm is most accurately accomplished using "mercury ring" piston prover calibrators. A calibrator of this type consists of a cylindrical glass tube, mounted vertically, and a plastic piston installed inside. The piston is free to move in the glass tube. There is a groove around the piston's circumference filled with mercury, sealing it in a virtually friction-free manner against the inside diameter of the glass tube.

Gas enters under the piston and is trapped by a valve, buoying the piston upward inside the tube. The edge of the piston registers a referenced zero and continues to travel up in the glass tube until it reaches the appropriate flow capacity. Timing the travel of the piston determines unit flow rates at each calibration point. The calibrator is corrected for temperature and pressure and compensated for the weight of the piston and friction in the line.

This method is demonstrated to offer a maximum uncertainty of ±0.25% of reading. Typically, National Institute of Standards and Technology (NIST) and equivalent international traceability standards require an uncertainty percentage ratio of 4 to 1; thus, an NIST traceable uncertainty of no better than ±1% may be claimed by a calibrating laboratory using such methods.

Calibrating larger flow rates of up to 5000 slpm (175 scfm) is facilitated by bell provers. The bell prover consists of a concentric inner and an outer cylindrical tank. The annular area between the concentric cylinders is filled with water or oil. An inverted bell is placed over the inner tank with its wall floating in the oil or water in the annular area between the two cylinders. During calibration at each reference point of the meter, gases are trapped under the bell. The rectilinear travel of the bell corresponds to sample volumes in timed intervals and is automatically recorded. Movement of the bell is usually detected by photoencoders or other sensing devices. Bells are precision balanced to maintain constant pressure and compensate for buoyancy throughout the collection stroke, and move freely, as gases are collected.

When more relaxed requirements of accuracy are acceptable, "transfer standards" will suffice. This means that a device, for example a mass flowmeter calibrated by a primary method, is used to calibrate flow instrumentation. As an example, a transfer standard calibrated for an uncertainty of ±1% may permit ±4% of traceable results.

Recalibration periods of mass flowmeters are based on industry standards. For example, in pharmaceutical processes, a period of six months is common. In industrial applications, depending on the industry, periods of six months to one year are recommended. When periodic recalibrations are performed, "as found" readings are recorded as well.

Liquid Calibrations

More recently, manufacturers developed bypass-type mass flowmeters and controllers for liquid microflow capacities. This requires calibration of microliter order of magnitude capacities of water. Ultra low liquid flow calibration is done by timed collection and weighing of water directly in a receptacle of a suitable pharmaceutical balance. Care should be taken to eliminate errors due to evaporation during sampling.

Small water flowmeters of up to 20 ml/min capacities are calibrated volumetrically. At steady state, flow water is delivered into an NIST-traceable, certified volumetric buret while timing appropriate volumetric segments. For meters with flow rates of a few liters per minute, an NIST-traceable, certified graduated cylinder is used.

Larger flow rates of liquids are calibrated at a steady-state flow of water by employing metering pumps into weighing tanks. Flows of up to 38 cmpm (10,000 gal/min) are accomplished through pipes with diameters of up to 16 in.

Collections of samples are timed, computing average flow through the meter, typically using ten or more points between 10 and 100% of capacity.

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2. King, L. V., On the convection of heat from small cylinders in a stream of fluid, *Philos. Trans. Royal Soc. of London*, Series A, 214, 373–432, 1914.

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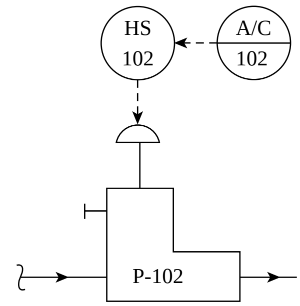
2.14 Metering Pumps

R. SIEV (1969, 1982) **B. G. LIPTÁK** (1995) **W. H. BOYES** (2003)



Proportioning Pump with Automatic and Manual Stroke Control
Flow Sheet Symbol

Types	A. Peristaltic (including progressive cavity) B. Piston or plunger types (provided with packing glands) C. Diaphragm or glandless types (mechanical, hydraulic, double-diaphragm, and pulsator designs)
Capacity	A. 0.0005 ccm to 20 GPM (90 l/min) B. 0.001 GPH to 280 GPM (0.005 lph to 1250 l/min) C. Mechanical diaphragms, from 0.01 to 50 GPH (0.05 to 3.7 l/min); mechanical bellows, from 0.01 to 250 GPH (0.05 to 18 l/min); others, from 0.01 to 800 GPH (0.05 lph to 60 l/min); pulsator pumps, from 30 to 1800 GPH (2 to 130 l/min); air-operated double diaphragm pumps, 0.0 to 275 GPM (1041 l/min)
Error (Inaccuracy)	A. ±0.1 to ±0.5% of full scale over a 10:1 range B. and C. ±0.25 to ±1% of full scale over a 10:1 range; can be as good as ±0.1% full scale at 100% stroke and tends to drop as stroke is reduced
Maximum Discharge Pressure:	A. 50 PSIG (3.5 bars) B. 50,000 PSIG (3450 bars) C. Mechanical bellows, up to 75 PSIG (5 bars); mechanical diaphragm, up to 300 PSIG (21.1 bars); hydraulic Teflon® diaphragm, 1500 PSIG (104 bars); pulsator pumps, up to 5000 PSIG (345 bars); hydraulic metallic diaphragms, up to 40,000 PSIG (2750 bars)
Maximum Operating Temperature	A. –70 to 600°F (–57 to 315°C) B. Jacketed designs, up to about 500°F (260°C) C. Units containing hydraulic fluids can handle from –95 to 360°F (–71 to 182°C), Teflon® and Viton® diaphragms are limited to 300°F (150°C), and neoprene and Buna N are limited to 200°F (92°C); the metal bellow and the remote head designs can operate from cryogenic to 1600°F (870°C)
Materials of Construction	A. Neoprene, Tygon, Viton®, silicone B. Cast iron, steel, stainless steel, Hastelloy® C, Alloy 20®, Carpenter 20, Monel®, nickel, titanium, glass, ceramics, PTFE, Teflon, PVC, Kel-F®, PVDF, PFA, Penton, polyethylene, and other plastics C. Polyethylene, Teflon, PVC, Kel-F®, Penton, steel, stainless steel, Carpenter 20, Monel®, Hastelloy® B & C
Cost	A. $200 to $800 B. $1000 to $6000 C. $1000 to $12,000, depending on type and service configuration
Partial List of Suppliers	Advantage Controls Inc. (C) (www.advantagecontrols.com) Alldos Inc. (www.alldos.com) (C) American LEWA Inc. (www.americanlewa.com) (A, B, C)

ARO Div. Ingersoll Rand (www.arozone.com) (C)
Barnant Co. (www.barnant.com) (A)
Blue-White Industries (www.bluwhite.com)
Bran & Luebbe Inc. (www.branluebbe.com)
Clark-Cooper Corp. (www.clarkcooper.com) (B, C)
Cole-Parmer Instrument Co. (www.coleparmer.com)
Crane Chem/Meter (www.chempump.com) (C)
Flo-Tron Inc. (B)
Fluid Metering Inc. (www.fluidmetering.com) (B)
Fluorocarbon Co. (www.fluorocarbon.co.uk)
Gerber Industries
Haskel International (www.haskel.com)
Hydroflow Corporation
Iwaki-Walchem (www.iwakiwalchem.com) (C)
Jaeco (www.jaeco.com)
Jesco America Inc. (www.jescoamerica.com) (C)
Linc Mfg. (B—pneumatic)
Milton Roy Flow Systems
  Liquid Metronics Inc. (www.lmipumps.com)
  Milton Roy (www.miltonroy.com) (B, C)
Neptune Chemical Pump Co. (www.neptune1.com) (B, C)
Plast-O-Matic Valves Inc. (www.plastomatic.com)
ProMinent Fluid Controls (www.prominent.cc) (C)
Pulsafeeder Inc. (www.pulsafeeder.com) (C)
Ruska Instrument Corp. (www.ruska.com)
Seepex (A) (www.seepex.com)
S J Control Inc. (www.sjcontrols.com)
Tuthill (www.tuthill.com) (B, C)
Valcor Scientific (www.valcor.com)
Wallace & Tiernan Inc. (B, C) (www.wallace-tiernan.com)

A metering pump is a positive-displacement pump providing a predictable and accurate rate of process fluid flow. Normally, the application design, specification, and use of pumps are the concern of mechanical engineers and machinery designers. Metering pumps, however, are sometimes used to actually measure or control flow rate, and in many cases they are the final control elements in an instrumentation loop. Therefore, the instrument engineer should be familiar with their operation and application.

Some controlled-volume pumps (as metering pumps are sometimes called) are designed to meet the needs of just one particular application, such as adding sodium hypochlorite to a swimming pool or providing chemical reagents to a chromatograph. Thus, each industry has its own particular types of metering pumps that could be classified by their applications. A better way of classifying metering pumps, however, is to distinguish them by their design. Any positive-displacement pump, due to its volumetric mode of fluid transfer, can be used as a metering pump. In practice, however, only those positive-displacement pumps that have no, or only very little, internal and/or external leakage can provide the precision and accuracy that are normally required of a metering pump.

The three basic metering pump designs are the peristaltic, piston, and diaphragm types. They are all positive-displacement devices used for the precise charging of corrosive, radioactive, toxic, flammable, or otherwise difficult fluids such as slurries, melts, liquefied gases, or liquid metals. They are used either in a controlled-volume metering mode or in a mixing-proportioning mode. The piston or plunger designs are provided with a packing gland, while the diaphragm or bellows designs are also referred to as glandless. The pulsator pump is a special variety of the glandless design. The actuators can adjust either the speed or the stroke, and the controls used for stroke adjustment include micrometers, positioners, and reversing motors with slide-wire feedback.

PERISTALTIC PUMPS

Peristaltic action is similar to the operation of the intestines and other hollow, muscular structures in which the successive contraction of the muscular fibers of their walls forces their content forward. In the peristaltic pump, the fluid is moved forward by progressively squeezing a flexible container from the entrance to discharge. This container is usually a tube that can be made out of any material that possesses sufficient resiliency to allow it to recover to its original shape immediately after compression. A variety of methods are employed for squeezing the tube (or container) to produce flow, including

1. Rollers that are connected to a rotating body squeeze the tubing against a circular housing (see Figure 2.14a)
2. Rollers that are driven by a chain drive squeeze tubes against a flat plate

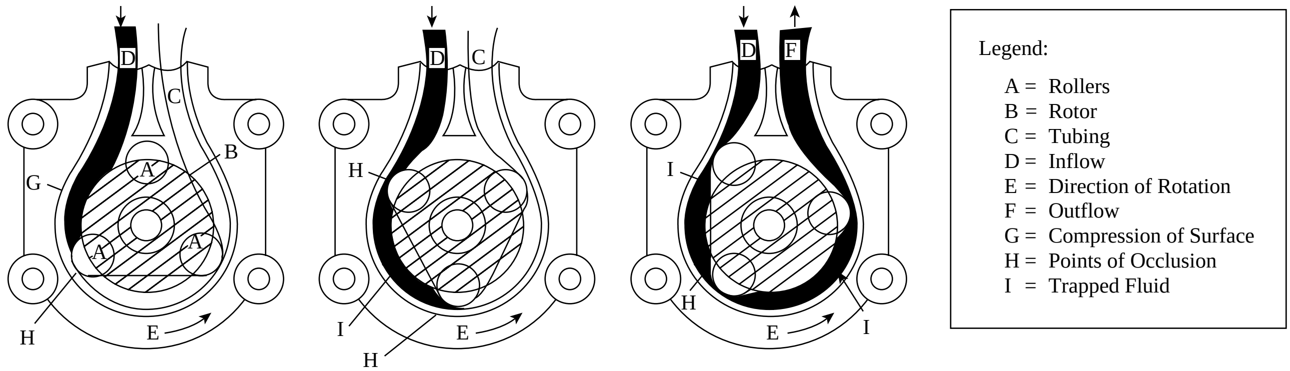


FIG. 2.14a
The three-roller design prevents backflow and eliminates the need for check valves. (Masterflex® is a registered trademark of Cole-Parmer Instrument Co.)

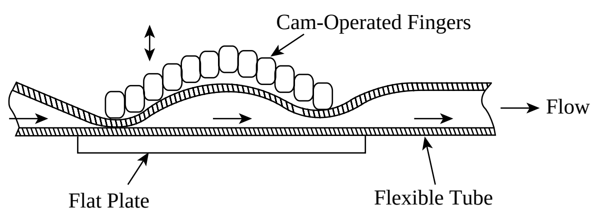


FIG. 2.14b
Peristaltic pump with cam-operated fingers.

3. Cam-operated fingers successively squeeze the tubing against a flat surface (see Figure 2.14b)
4. A rotating wobbling cam squeezes a tube against a flat plate

The plastic hose or tubing provides an external, tight, sanitary, and easily cleanable and replaceable container. It must be remembered that the tube is the only component of the pump that comes into contact with the fluid. A plastic material usually can be found that is suitable for even the most corrosive and abrasive application. However, the use of plastic tubing also places severe limits on the capability of the peristaltic pump. These pumps can furnish only low flow rates and low-pressure heads.

The peristaltic pump has found particularly large acceptance in medical and biochemical fields where high accuracy, low flow rates, inherent enclosure of the fluid, and sterilization are prime requirements. The flow rate of the peristaltic pump can be adjusted by changing the speed of the squeezing mechanism. Commonly, 50/60-Hz, 100/110-V electrical motors provide power to these pumps. Air-operated and electrical explosion-proof motors are also available.

Another peristaltic pump employs a plastic liner separating a rotating cam from the pumped fluid. This allows the use of a cam-type positive-displacement pump for metering service but prevents any external leakage. Higher pressures and flow rates can be obtained from this pump, but the advantages of the flexible tubing are lost.

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. These pumps are useful in pumping highly viscous fluids such as adhesives, sludge, and slurries such as chocolate, tomato paste, and similar highly viscous liquids.

PISTON PUMPS

The piston pump employs a piston or plunger that moves with a reciprocating motion within a chamber. A fixed volume of liquid is delivered with each stroke. The flow rate is a function of piston diameter, chamber length, and piston speed. Check valves located at the pump inlets and outlets are required to prevent backflow. A schematic of a typical piston pump is shown in Figure 2.14c. The piston produces pressure in only one direction; therefore, the flow produced by plunger pumps (as piston pumps are sometimes called) is pulsating. If the

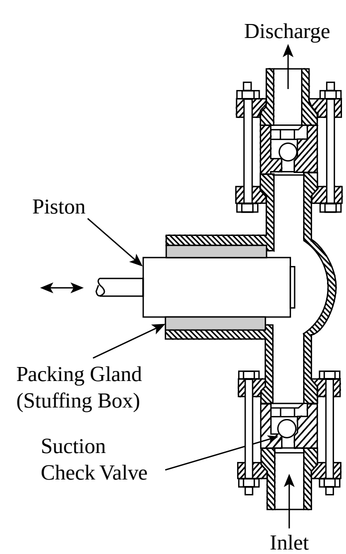


FIG. 2.14c
Piston pump schematic.

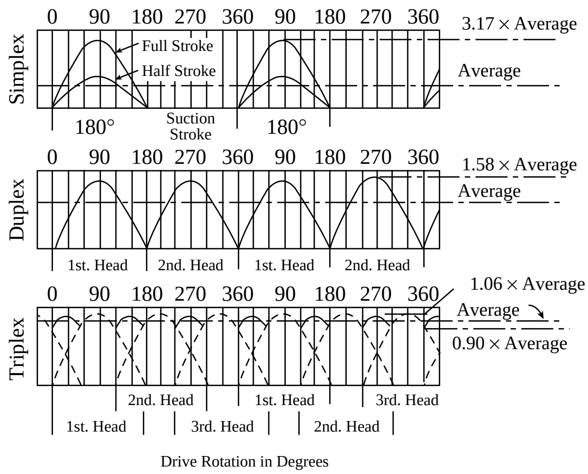


FIG. 2.14d
Multiple pistons tend to dampen pressure fluctuations.

pulsating flow characteristics are undesirable, a damping reservoir (accumulator) should be installed in the discharge line of the pump. Another method available to reduce pulsation is to use a pump that employs more than one chamber/piston combination in parallel. Pumps having as many as four chambers (cylinders) are commercially available. These multiple-piston pumps are called *duplex pumps* if they have two pistons, *triplex* if they have three, and so on (see Figure 2.14d).

The construction materials of a piston pump's components must be selected with care, because its housing, piston, piston packing, valve body, and valve seat all come into intimate contact with the process fluid.

The displacement of the pump is the area of the plunger multiplied by the stroke length. This is not the volume that is actually delivered, because some of the fluid slips back into the cylinder while the check valves are closing. Worn valves and fluid compressibility at high discharge pressures further reduce the volumetric efficiency (usually around 95%) of plunger pumps. Check valve leakage can be reduced by installing two check valves in series at both the pump suction and discharge. Volumetric efficiency should not be taken as metering accuracy, because leakage is repeatable and can be zeroed out by calibration. Therefore, in properly maintained and calibrated metering pumps, the measurement error will be much less than the leakage.

The plunger packing must be carefully selected not only to minimize leakage and wear but also for lubrication, cooling, sterilization, and flushing. This pump design can deliver both high flow rates and high discharge pressures. The smaller the plunger diameter, the greater the possible discharge pressure.

When metering abrasive slurries such as kaolin, diatomaceous earth, and metal-based catalysts, it is necessary to introduce a clean flushing fluid. This flushing fluid flows from the piston–cylinder cavity into the process fluid (Figure 2.14e), thereby keeping the piston and its packing clean during both the suction and discharge strokes. This flushing action prevents

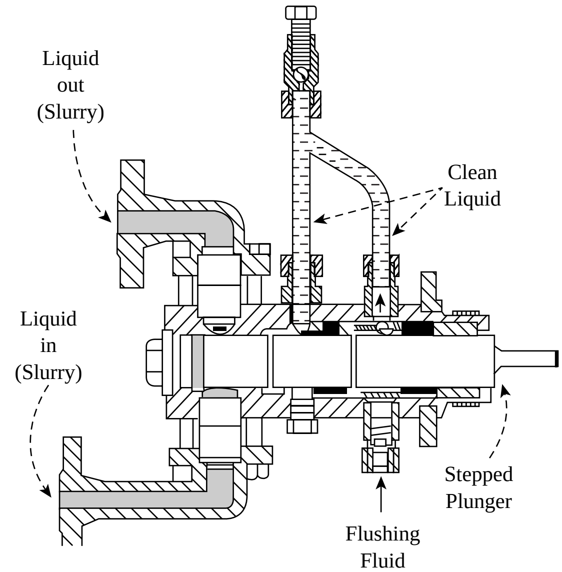


FIG. 2.14e
Flushing fluid keeps the packing free of solids on slurry services.[1]

the slurry from reaching the plunger packing. The metering action can still take place, because the mix proportion between the slurry and the flushing liquid is kept constant.

DIAPHRAGM PUMPS

The diaphragm or membrane pump uses a flexible member to transmit a pulsating force to the pumped fluid without allowing external leakage such as what might occur past the piston pump's packing. Like the piston pump, inlet and exit check valves are used to direct the flow. The diaphragm may be soft, made of Teflon®, neoprene, or a similar material, or it can be hard and made of metal. The diaphragm may be moved directly by a piston as in a reciprocating piston pump (see Figure 2.14f). This type, which may also employ a

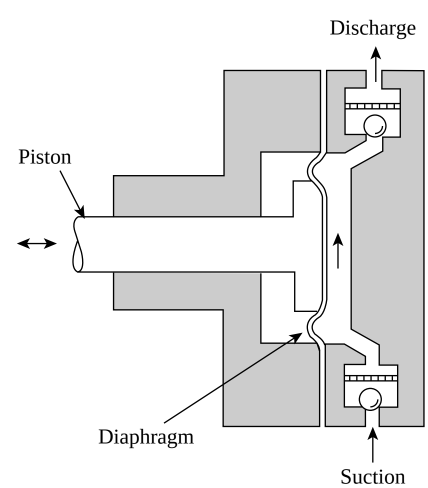


FIG. 2.14f
Direct-driven diaphragm pump.

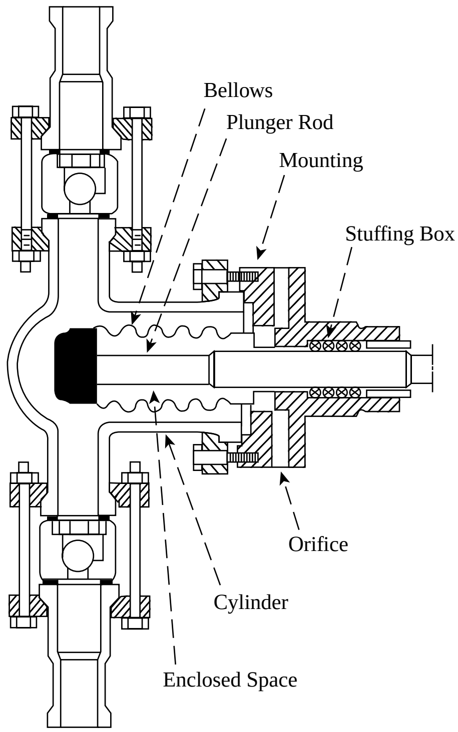


FIG. 2.14g
For extreme temperature applications the bellows-type, direct, mechanically actuated metering pump is a good choice.[1]

bellows instead of a diaphragm (Figure 2.14g), generally has a pressure limitation of about 125 PSIG (8.5 bars).

The glandless metering pumps can handle toxic, corrosive, radioactive, high-purity, odorous, volatile, and abrasive materials. The direct-actuated diaphragm designs are the least expensive and are suited for low-pressure, low-flow-rate services. The mechanically actuated bellows design can deliver more flow and is well suited for vacuum or extreme temperature services. For higher temperatures and corrosion resistance, metal bellows are used.

Hydraulic-Actuated Metering Pumps

In these designs, the forces delivered by hydraulic oil that is pumped by a reciprocating piston pump replace the direct mechanical forces on the diaphragm. The other side of the diaphragm is exposed to the process fluid (Figure 2.14h); therefore, the diaphragm is inherently balanced, being exposed to equal pressures on both of its sides. The support plates serve to keep the diaphragm deflections well within the endurance limits of the diaphragm material. This guarantees long useful life.

Metallic diaphragms can be damaged by dirt particles, and plastic diaphragms cannot handle high pressures and temperatures. Where a reliable seal is essential (for example, for pharmaceutical or liquid chlorine services), the double-diaphragm design is recommended (Figure 2.14i). In these designs, the diaphragm rupture can be visually observed if a sight glass is installed in the intermediate chamber, which is

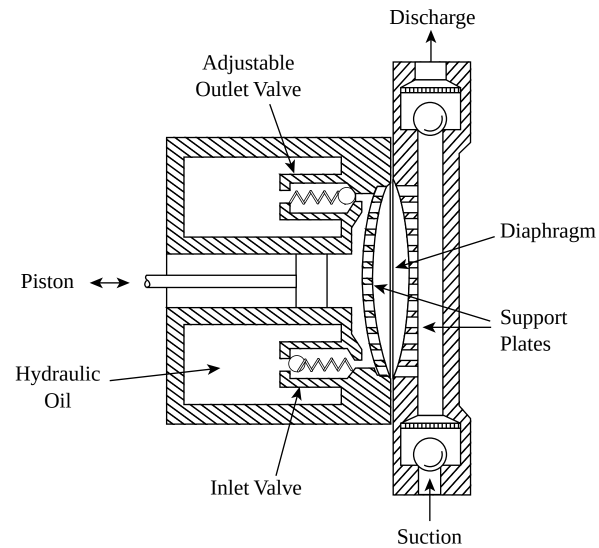


FIG. 2.14h
Oil-driven diaphragm pump.

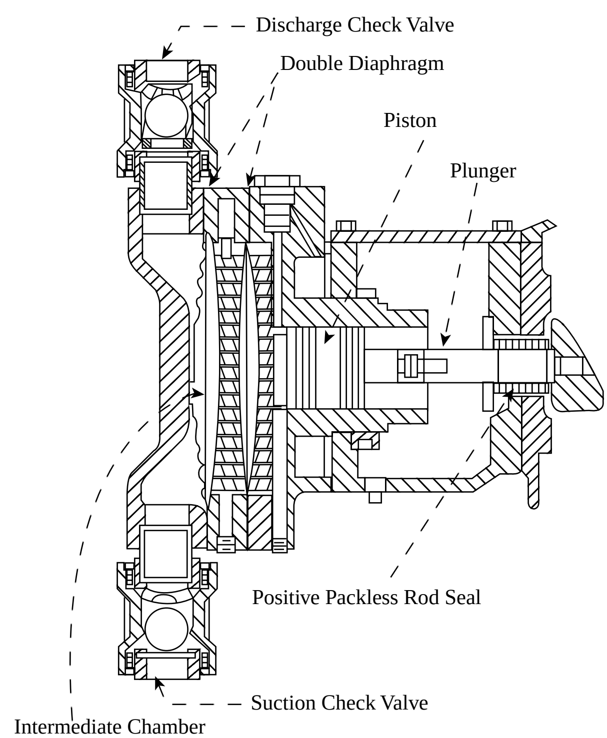


FIG. 2.14i
Double diaphragm design provides improved seal.

filled with a liquid of a preselected pH reference color. If the process-side diaphragm is damaged, the leakage of process fluid into the intermediate chamber changes the pH and thereby changes the color of the intermediate fluid. The materials exposed to the pumped fluid—diaphragm, housing, and valves—must be carefully selected for the application.

As with the piston pump, the flow is pulsating but may be smoothed by multiple diaphragms and/or by the use of a

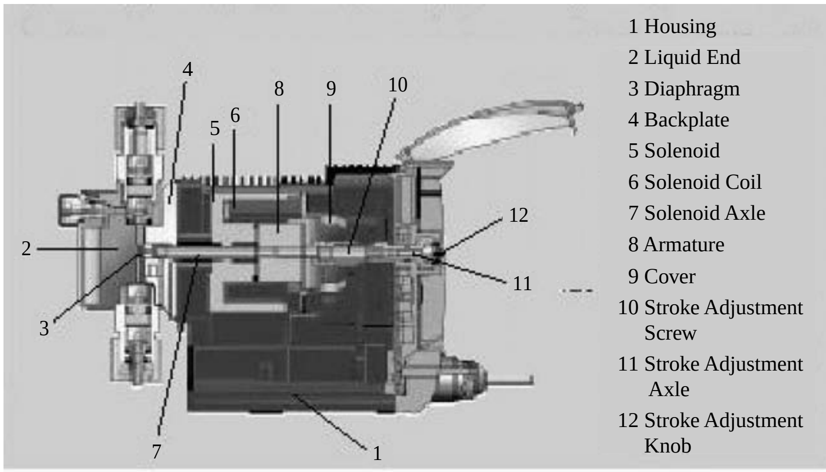


FIG. 2.14j
Solenoid-driven diaphragm pump is one of the most commonly used types for most metering pump applications. (Courtesy of Prominent Fluid Controls Co.)

damping reservoir. Check valve leakage provides the same problem for the diaphragm pump as it did for the piston pump.

The slave fluid's pulsation rate is varied by adjusting the piston pump's stroke length, altering the eccentricity of the crank or changing the duration of the stroke by diverting a portion of each stroke to idle motion by mechanical or hydraulic means. Because slave hydraulic fluid leakage does not affect the metered rate of flow, many variations of the standard reciprocating piston pump can be used.

When it is desired to keep the metering pump away from hot processes, a remote head design is frequently used in which the check valve assembly remains in the process pipe while the diaphragm and pump are located at some distance away. The connecting pipe is filled with a column of the process fluid, and a temperature gradient through this column of liquid isolates the diaphragm and its hydraulic fluid from the hot process.

Solenoid-Driven Metering Pumps

Since the early 1970s, by far the most common forms of metering pump have been the peristaltic and the solenoid-driven-diaphragm metering pumps. The diaphragm metering pump described previously is fitted with a shaft that extends behind the pump head to a mechanical stop, which is adjustable to control the stroke length (Figure 2.14j). This shaft passes through the coil of a solenoid. The solenoid is actuated based on either a timer or an external input, and each actuation of the solenoid produces one pulse of the diaphragm. These pumps are widely used in industrial water treatment, chemical feed systems, and municipal and utility water treatment. They can be either manual, with the stroke and stroke length controlled at the pump, or they can be proportioning, based on an input signal from a controller. They have the same mechanical constraints as hydraulically driven diaphragm metering pumps.

Pulsator-Head Pumps

These pumps can be valuable when very difficult fluids are being metered, such as boiling sulfuric acid, pyrophoric fluids, fluorinated hydrocarbons, and slurries suspended in Freon®. In this design, hydraulic oil is pumped through the hollow cavity of the pulsator support into two hermetically sealed diaphragms called *pulsators*. As the pulsator elements expand, they displace the process fluid from the pressure chamber. When the hydraulic oil is exhausted from the pulsator, fresh process fluid is drawn into the pressure chamber through the suction port (Figure 2.14k). Although the illustration shows only one pulsator, two normally are used to smooth out the flow. The alternate expansion and contraction of the pulsators causes the pumping action. The inner pulsator is usually Buna N, and the outer one is selected to match the fluid being pumped.

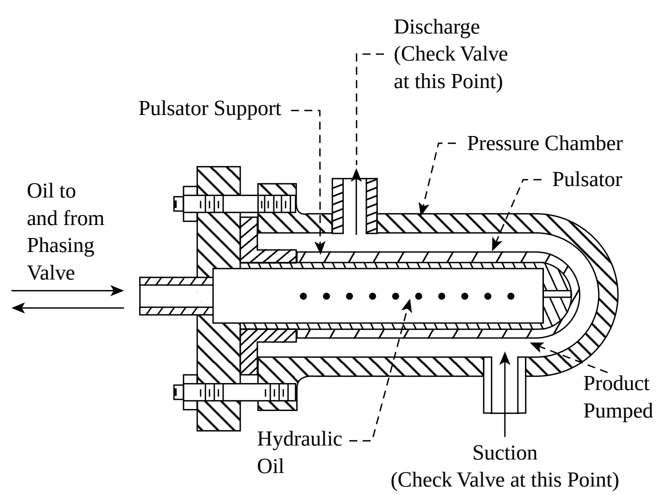


FIG. 2.14k
The pulsator-type metering pump.[1]

The pulsator pump produces a substantially pulsation-free, infinitely adjustable flow rate, which is set by the variable-volume oil pump. In hazardous areas, the hydraulic fluid can be pumped from a remote location, thereby removing all electrical components from the process area. The pump can be easily sterilized, because only the outside of the pulsator is exposed to contamination. Consequently, the pump can be cleaned by removing just the pressure chamber.

PROPORTIONING PUMPS

Proportioning pumps are used when several process streams need to be mixed in some preset proportion. These can be continuous mixing processes or batch processes in which the ingredients are simultaneously fed. In digital batch blending, it is the cycle time and the pump size that set the number of pump strokes or pulses per batch. For example, if the cycle time is 30 min and the amount to be charged is 60 gal, a pump capacity of 2 GPM is required. If this pump operates at a speed of 60 strokes per minute, then 1800 strokes or pulses would represent the 60 gal of batch charge. The pump pulse transmitter transmits the pulses and, when the 1800 count is reached, the batch controller stops the pump.

The proportioning of several process streams can be achieved in many different ways, depending on the hardware used. One possible solution is to operate several metering pumps in parallel. When using piston or diaphragm pumps, it is also possible to place multiple heads on the same drives, which will also achieve the same proportioning goal. On idle motion pumps, the proportioning adjustments can be achieved by varying the stroke duration.

The peristaltic pumps are natural proportioning devices. One can lay as many as 23 tubes of various sizes on a flat plate, and the finger or chain-driven rollers of the peristaltic pump will squeeze all tubes simultaneously and at the same speed. In this configuration, the tube sizes set the ratios between flows, whereas the total pumping rate for the mix is set by the motor speed.

All proportioning and digital batch-blending controls use modern, computer-compatible, microprocessor-based controls.

CONTROLLERS

Pulse-Input Type

Most modern metering pumps have on-board controllers that accept pulses generated by external controllers or sensors. These inputs are usually either a two-wire switch closure (such as a reed switch or SPST relay) or a powered, three-wire switch closure for a transistor switch input such as a Hall effect sensor or a Wiegand sensor. Many pumps can take the pulse input directly from a flow sensor, such as a paddle wheel or a pulse-contact head water meter, and scale it internally and use the raw sensor signal to proportionally control the stroke rate of the pump. A manual stroke length adjustment in the most commonly used solenoid-driven diaphragm metering pumps still performs dosage control in most cases.

Analog-Input Type

Some modern metering pumps are equipped with on-board signal conditioners to accept an incoming analog signal (4- to 20-mA DC, 1 to 5 VDC, and others) and convert that signal to an internal scaled pulse to operate the metering pump.

Start/Stop Type

In some industries, particularly industrial water treatment and boiler control, manual start/stop metering pumps are regularly used. External controllers are usually supplied that turn AC power to these pumps on and off for varying lengths of time, depending on an external signal from either a flow sensor or a pH, conductivity, or oxidation-reduction-potential (ORP) controller. The pump then becomes a proportioning feeder.

CONCLUSION

Each metering pump discussed has its particular application. Piston pumps are used to deliver high pressures. They require check valves and produce pulsating flows that can be damped. Diaphragm pumps are utilized in the medium-pressure range. The membrane serves as a moving partition between the mechanical or hydraulic drive and the process fluid. Rotary and pulsator pumps furnish pulsation-free high flow rates and are suitable for high-viscosity service. The accuracy of rotary pumps is a function of the clearances between the rubbing surfaces. This generally results in low precision, so rotary pumps are not considered to be metering devices. Peristaltic pumps are very accurate; they can handle extremely small flows, are self-priming, and require no seals or check valves.

If one is responsible for the operation and maintenance of a metering pump, one must be aware that a pump differs in many aspects from other flowmeters. For example, the pump motor must be lubricated periodically, and the pump must not be operated without liquid in it. The inlet piping must be designed to prevent cavitation. Running a pump dry or cavitating it will cause damage.

A metering pump should be calibrated, not only before it is first used but also periodically during its operation. The calibration should duplicate fluid properties, suction and discharge pressures, and inlet and outlet piping configuration.

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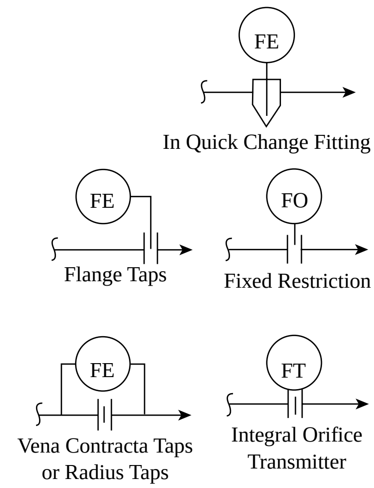
2.15 Orifices

W. H. HOWE (1969) **B. G. LIPTÁK** (1995), **REVIEWED BY S. RUDBÄCH**
J. B. ARANT (1982, 2003)



Flow Sheet Symbol

Design Pressure	For plates, limited by readout device only; integral orifice transmitter to 1500 PSIG (10.3 MPa)
Design Temperature	This is a function of associated readout system, only when the differential-pressure unit must operate at the elevated temperature. For integral orifice transmitter, the standard range is –20 to 250°F (–29 to 121°C).
Sizes	Maximum size is pipe size
Fluids	Liquids, vapors, and gases
Flow Range	From a few cubic centimeters per minute using integral orifice transmitters to any maximum flow, limited only by pipe size
Materials of Construction	There is no limitation on plate materials. Integral orifice transmitter wetted parts can be obtained in steel, stainless steel, Monel®, nickel, and Hastelloy®.
Inaccuracy	The orifice plate; if the bore diameter is correctly calculated, prepared, and installed, the orifice can be accurate to ±0.25 to ±0.5% of actual flow. When a properly calibrated conventional d/p cell is used to detect the orifice differential, it will add ±0.1 to ±0.3% of full-scale error. The error contribution of properly calibrated "smart" d/p cells is only 0.1% of actual span.
Smart d/p Cells	Inaccuracy of ±0.1%, rangeability of 40:1, built-in PID algorithm
Rangeability	If one defines rangeability as the flow range within which the combined flow measurement error does not exceed ±1% of actual flow, then the rangeability of conventional orifice installations is about 3:1 maximum. When using intelligent transmitters with automatic switching capability between the "high" and the "low" span, the rangeability can approach 10:1.
Cost	A plate only is $100 to $300, depending on size and materials. For steel orifice flanges from 2 to 12 in. (50 to 300 mm), the cost ranges from $250 to $1200. For flanged meter runs in the same size range, the cost ranges from $500 to $3500. The cost of electronic or pneumatic integral orifice transmitters is between $1500 and $2500. The cost of d/p transmitters ranges from $1000 to $2500, depending on type and "intelligence."
Partial List of Suppliers	ABB Process Automation (www.abb.com/processautomation) (incl. integral orifices) Daniel Measurement and Control (www.danielind.com) (orifice plates and plate changers) The Foxboro Co. (www.foxboro.com) (incl. integral orifices) Honeywell Industrial Control (www.honeywell.com/acs/cp) Meriam Instrument (www.meriam.com) (orifice plates) Rosemount Inc. (www.rosemount.com) Tri-Flow Inc. (www.triflow.com)

In addition, orifice plates, flanges and accessories can be obtained from most major instrument manufacturers.

HEAD-TYPE FLOWMETERS

Head-type flowmeters compose a class of devices for fluid flow measurement including orifice plates, venturi tubes, weirs, flumes, and many others. They change the velocity or direction of the flow, creating a measurable differential pressure or “pressure head” in the fluid.

Head metering is one of the most ancient of flow detection techniques. There is evidence that the Egyptians used weirs for measurement of irrigation water in the days of the Pharaohs and that the Romans used orifices to meter water to households in Caesar’s time. In the 18th century, Bernoulli established basic relationship between pressure head and velocity head, and Venturi published on the flowtube bearing his name. However, it was not until 1887 that Clemens Herschel developed the commercial venturi tube. Work on the conventional orifice plate for gas flow measurement was commenced by Weymouth in the United States in 1903. Recent developments include improved primary elements, refinement of data, more accurate and versatile test and calibrating equipment, better differential-pressure sensors, and many others.

Theory of Head Meters

Head-type flow measurement derives from Bernoulli’s theorem, which states that, in a flowing stream, the sum of the pressure head, the velocity head, and the elevation head at one point is equal to their sum at another point in the direction of flow plus the loss due to friction between the two points. Velocity head is defined as the vertical distance through which a liquid would fall to attain a given velocity. Pressure head is the vertical distance that a column of the flowing liquid would rise in an open-ended tube as a result of the static pressure.

This principle is applied to flow measurement by altering the velocity of the flowing stream in a predetermined manner, usually by a change in the cross-sectional area of the stream. Typically, the velocity at the throat of an orifice is increased relative to the velocity in the pipe. There is a corresponding increase in velocity head. Neglecting friction and change of elevation head, there is an equal decrease in pressure head (Figure 2.15a). This difference between the pressure in the pipe just upstream of the restriction and the pressure at the throat is measured. Velocity is determined from the ratio of

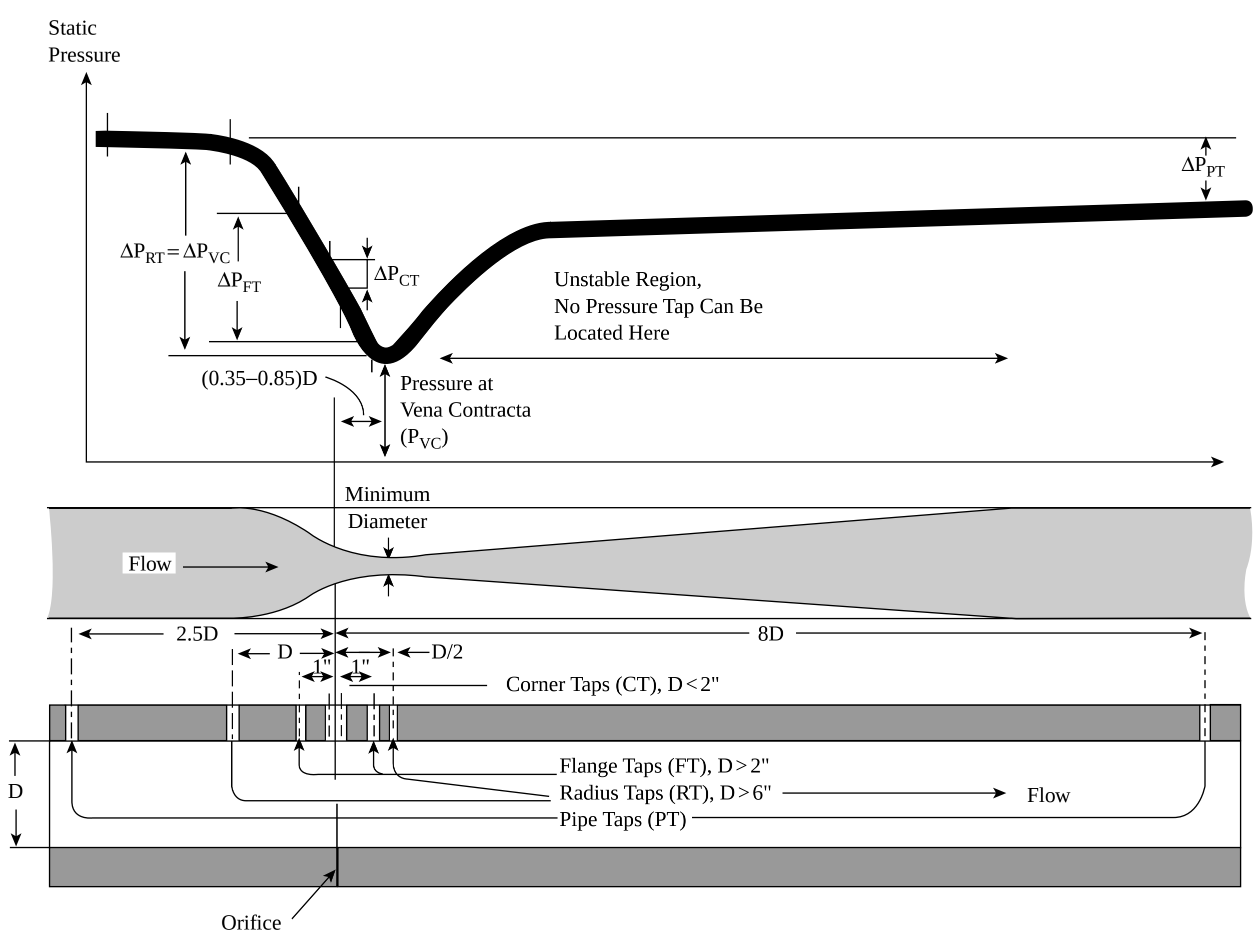


FIG. 2.15a
Pressure profile through an orifice plate and the different methods of detecting the pressure drop.

the cross-sectional areas of pipe and flow nozzle, and the difference of velocity heads given by differential-pressure measurements. Flow rate derives from velocity and area. The basic equations are as follows:

$$V = k\sqrt{\frac{h}{\rho}} \qquad \textbf{2.15(1)}$$

$$Q = kA\sqrt{\frac{h}{\rho}} \qquad \textbf{2.15(2)}$$

$$W = kA\sqrt{h\rho} \qquad \textbf{2.15(3)}$$

where

V = velocity
Q = volume flow rate
W = mass flow rate
A = cross-sectional area of the pipe
h = differential pressure between points of measurement
ρ = the density of the flowing fluid
k = a constant that includes ratio of cross-sectional area of pipe to cross-sectional area of nozzle or other restriction, units of measurement, correction factors, and so on, depending on the specific type of head meter

For a more complete derivation of the basic flow equations, based on considerations of energy balance and hydrodynamic properties, consult References 1, 2, and 3.

Head Meter Characteristics

Two fundamental characteristics of head-type flow measurements are apparent from the basic equations. First is the square root relationship between flow rate and differential pressure. Second, the density of the flowing fluid must be taken into account both for volume and for mass flow measurements.

The Square Root Relationship This relationship has two important consequences. Both are primarily concerned with readout. The primary sensor (orifice, venturi tube, or other device) develops a head or differential pressure. A simple linear readout of this differential pressure expands the high end of the scale and compresses the low end in terms of flow. Fifty percent of full flow rate produces 25% of full differential pressure. At this point, a flow change of 1% of full flow results in a differential pressure change of 1% of full differential. At 10% flow, the total differential pressure is only 1%, and a change of 1% of full scale flow (10% relative change) results in only 0.2% full scale change in differential pressure. Both accuracy and readability suffer. Readability can be improved by a transducer that extracts the square root of the differential pressure to give a signal linear with flow rate. However, errors in the more complex square root transducer tend to decrease overall accuracy.

For a large proportion of industrial processes, which seldom operate below 30% capacity, a device with pointer or pen motion that is linear with differential pressure is generally adequate. Readout directly in flow can be provided by a square root scale. Where maximum accuracy is important, it is generally recommended that the maximum-to-minimum flow ratio shall not exceed 3:1, or at the most 3.5:1, for any single head-type flowmeter. The high repeatability of modern differential-pressure transducers permits a considerably wider range for flow control where constancy and repeatability of low rate are the primary concern. However, where flow variations approach 10:1, the use of two primary flow units of different capacities, two differential-pressure sensors with different ranges, or both is generally recommended. It should be emphasized that the primary head meter devices produce a differential pressure that corresponds accurately to flow over a wide range. Difficulty arises in the accurate measurement of the corresponding extremely wide range of differential pressure; for example, a 20:1 flow variation results in a 400:1 variation in differential pressure.

The second problem with the square root relationship is that some computations require linear input signals. This is the case when flow rates are integrated or when two or more flow rates are added or subtracted. This is not necessarily true for multiplication and division; specifically, flow ratio measurement and control do not require linear input signals. A given flow ratio will develop a corresponding differential pressure ratio over the full range of the measured flows.

Density of the Flowing Fluid Fluid density is involved in the determination of either mass flow rate or volume flow rate. In other words, head-type meters *do not* read out directly in either mass or volume flow (weirs and flumes are an exception, as discussed in Section 2.31). The fact that density appears as a square root gives head-type metering an actual advantage, particularly in applications where measurement of mass flow is required. Due to this square root relationship, any error that may exist in the value of the density used to compute mass flow is substantially reduced; a 1% error in the value of the fluid density results in a 0.5% error in calculated mass flow. This is particularly important in gas flow measurement, where the density may vary over a considerable range and where operating density is not easily determined with high accuracy.

β (Beta) Ratio Most head meters depend on a restriction in the flow path to produce a change in velocity. For the usual circular pipe and circular restriction, the β ratio is the ratio between the diameter of the restriction and the inside diameter of the pipe. The ratio between the velocity in the pipe and the velocity at the restriction is equal to the ratio of areas or β^2. For noncircular configurations, β is defined as the square root of the ratio of area of the restriction to area of the pipe or conduit.

Reynolds Number

The basic equations of flow assume that the velocity of flow is uniform across a given cross section. In practice, flow velocity at any cross section approaches zero in the boundary layer adjacent to the pipe wall and varies across the diameter. This flow velocity profile has a significant effect on the relationship between flow velocity and pressure difference developed in a head meter. In 1883, Sir Osborne Reynolds, an English scientist, presented a paper before the Royal Society proposing a single, dimensionless ratio (now known as Reynolds number) as a criterion to describe this phenomenon. This number, Re, is expressed as

$$R_e = \frac{VD\rho}{\mu} \qquad \textbf{2.15(4)}$$

where
V = velocity
D = diameter
ρ = density
μ = absolute viscosity

Reynolds number expresses the ratio of inertial forces to viscous forces. At a very low Reynolds number, viscous forces predominate, and inertial forces have little effect. Pressure difference approaches direct proportionality to average flow velocity and to viscosity. At high Reynolds numbers, inertial forces predominate, and viscous drag effects become negligible.

At low Reynolds numbers, flow is laminar and may be regarded as a group of concentric shells; each shell reacts in a viscous shear manner on adjacent shells, and the velocity profile across a diameter is substantially parabolic. At high Reynolds numbers, flow is turbulent, with eddies forming between the boundary layer and the body of the flowing fluid and propagating through the stream pattern. A very complex, random pattern of velocities develops in all directions. This turbulent mixing action tends to produce a uniform average axial velocity across the stream. The change from the laminar flow pattern to the turbulent flow pattern is gradual, with no distinct transition point. For Reynolds numbers above 10,000, flow is definitely turbulent. The coefficients of discharge of the various head-type flowmeters changes with Reynolds number (Figure 2.15b).

The value for k in the basic flow equations includes a Reynolds number factor. References 1 and 2 provide tables and graphs for Reynolds number factor. For head meters, this single factor is sufficient to establish compensation in coefficient for changes in ratio of inertial to frictional forces and for the corresponding changes in flow velocity profile; a gas flow with the same Reynolds number as a liquid flow has the same Reynolds number factor.

Compressible Fluid Flow

Density in the basic equations is assumed to be constant upstream and downstream from the primary device. For gas or vapor flow, the differential pressure developed results in

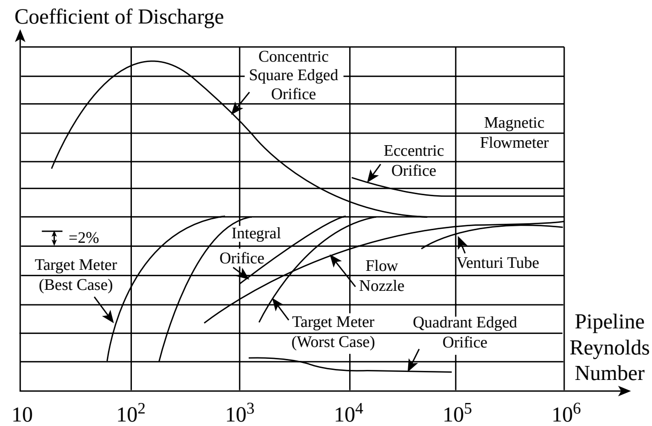


FIG. 2.15b
Discharge coefficients as a function of sensor type and Reynolds number.

a corresponding change in density between upstream and downstream pressure measurement points. For accurate calculations of gas flow, this is corrected by an *expansion factor* that has been empirically determined. Values are given in References 1 and 2. When practical, the full-scale differential pressure should be less than 0.04 times normal minimum static pressure (differential pressure, stated in inches of water, should be less than static pressure stated in PSIA). Under these conditions, the expansion factor is quite small.

Choice of Differential-Pressure Range

The most common differential-pressure range for orifices, venturi tubes, and flow nozzles is 0 to 100 in. of water (0 to 25 kPa) for full-scale flow. This range 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. Most differential-pressure-responsive devices develop their maximum accuracy in or near this range, and the maximum pressure loss—3.5 PSI (24 kPa)—is not serious in most applications. (As shown in Figure 2.27f, the pressure loss in an orifice is about 65% when a β ratio of 0.75 is used.) The 100-in. range permits a 2:1 flow rate change in either direction to accommodate changes in operating conditions. Most differential-pressure sensors can be modified to cover the range from 25 to 400 in. of water (6.2 to 99.4 kPa) or more, either by a simple adjustment or by a relatively minor structural change. Applications in which the pressure loss up to 3.5 PSI is expensive or is not available can be handled either by selection of a lower differential-pressure range or by the use of a venturi tube or other primary element with high-pressure recovery. Some high-velocity flows will develop more than 100 in. of differential pressure with the maximum acceptable ratio of primary element effective diameter to pipe diameter. For these applications, a higher differential pressure is indicated. Finally, for low-static-pressure (less than 100 PSIA) gas or vapor, a lower differential pressure is recommended to minimize the expansion factor.

Pulsating Flow and Flow "Noise"

Short-period (1 sec and less) variation in differential pressure developed from a head-type flowmeter primary element arises from two distinct sources. First, reciprocating pumps, compressors, and the like may cause a periodic fluctuation in the rate of flow. Second, the random velocities inherent in turbulent flow cause variations in differential pressure even with a constant flow rate. Both have similar results and are often mistaken for each other. However, their characteristics and the procedures used to cope with them are distinct.

Pulsating Flow The so-called pulsating flow from reciprocating pumps, compressors, and so on may significantly affect the differential pressure developed by a head-type meter. For example, if the amplitude of instantaneous differential-pressure fluctuation is 24% of the average differential pressure, an error of ±1% can be expected under normal operation conditions. For the pulsation amplitudes of 24, 48, and 98% values, the corresponding errors of ±1, ±4, and ±16% can be expected. The Joint ASME-AGA Committee on Pulsation reported that the ratio between errors varies roughly as the square of the ratio between differential-pressure fluctuations.

For liquid flow, there is indication that the average of the square root of the instantaneous differential pressure (essentially average of instantaneous flow signal) results in a lower error than the measurement of the average instantaneous differential pressure. However, for gas flow, extensive investigation has failed to develop any usable relationship between pulsation and deviation from coefficient beyond the estimate of maximum error.[4]

Operation at higher differential pressures is generally advantageous for pulsating flow. The only other valid approach to improve the accuracy of pulsating gas flow measurement is the location of the meter at a point where pulsation is minimized.

Flow "Noise" Turbulent flow generates a complex pattern of random velocities. This results in a corresponding variation or "noise" in the differential pressure developed at the pressure connections to the primary element. The amplitude of the noise may be as much as 10% of the average differential pressure with a constant flow rate. This noise effect is a complex hydrodynamic phenomenon and is not fully understood. It is augmented by flow disturbances from valves, fittings, and so on both upstream and downstream from the flowmeter primary element and, apparently, by characteristics of the primary element itself.

Tests based on average flow rate as accurately determined by static weight/time techniques (compared to accurate measurement of differential pressure including continuous, precise averaging of noise) indicate that the noise, when precisely averaged, introduces negligible (less than 0.1%) measurement error when the average flow is substantially constant (change of average flow rate is not more than 1% per second).[5] It should be noted that average differential pressure, not average flow (average of the square root of differential pressure), is measured, because the noise is developed by the random, not the average, flow.

Errors in the determination of true differential-pressure average 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. Where accuracy is a major concern, there must be no elements in the system that will develop a bias rather than a true average when subjected to the complex noise pattern of differential pressure.

Differential-pressure noise can be reduced by the use of two or more pressure-sensing taps connected in parallel for both high and low differential-pressure connections. This provides major noise reduction. Only minor improvement results from additional taps. Piezometer rings formed of multiple connections are frequently used with venturi tubes but seldom with orifices or flow nozzles.

THE ORIFICE METER

The orifice meter is the most common head-type flow measuring device. An orifice plate is inserted in the line, and the differential pressure across it is measured (Figure 2.15a). This section is concerned with the primary device (the orifice plate, its mounting, and the differential-pressure connections). Devices for the measurement of the differential pressure are covered in Chapters 3 and 5.

The orifice in general, and the conventional thin, concentric, sharp-edged orifice plate in particular, have important advantages that include being inexpensive manufacture to very close tolerances and easy to install and replace. Orifice measurement of liquids, gases, and vapors under a wide range of conditions enjoys a high degree of confidence based on a great deal of accurate test work.

The standard orifice plate itself is a circular disk; usually stainless steel, from 0.12 to 0.5 in. (3.175 to 12.70 mm) thick, depending on size and flow velocity, with a hole (orifice) in the middle and a tab projecting out to one side and used as a data plate (Figure 2.15c). The thickness requirement of the orifice plate is a function of line size, flowing temperature, and differential pressure across the plate. Some helpful guidelines are as follows.

By Size
- 2 to 12 in. (50 to 304 mm), 0.13 in. (3.175 mm) thick
- 14 in. (355 mm) and larger, 0.25 in. (6.35 mm) thick

By Temperature ≥600°F (316°C)
- 2 to 8 in. (50 to 203 mm), 0.13 in. (3.175 mm) thick
- 10 in. (254 mm) and larger, 0.25 in. (6.35 mm) thick

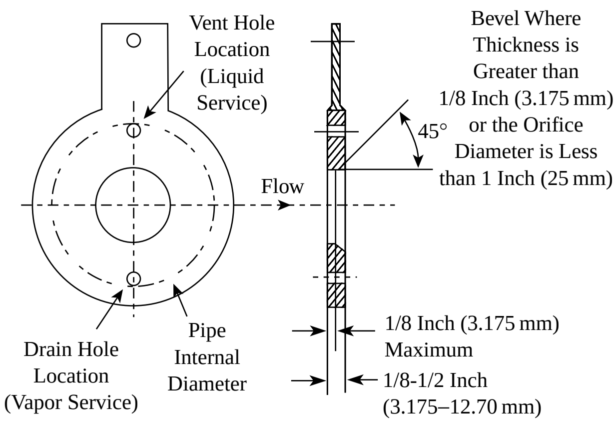


FIG. 2.15c
Concentric orifice plate.

Flow through the Orifice Plate

The orifice plate inserted in the line causes an increase in flow velocity and a corresponding decrease in pressure. The flow pattern shows an effective decrease in cross section beyond the orifice plate, with a maximum velocity and minimum pressure at the vena contracta (Figure 2.15a). This location may be from 0.35 to 0.85 pipe diameters downstream from the orifice plate, depending on β ratio and Reynolds number.

This flow pattern and the sharp leading edge of the orifice plate (Figure 2.15d) that produces it are of major importance. The sharp edge results in an almost pure line contact between the plate and the effective flow, with negligible fluid-to-metal friction drag at this boundary. Any nicks, burrs, or rounding of the sharp edge can result in surprisingly large measurement errors.

When the usual practice of measuring the differential pressure at a location close to the orifice plate is followed, friction effects between fluid and pipe wall upstream and downstream from the orifice are minimized so that pipe roughness has minimum effect. Fluid viscosity, as reflected in Reynolds number, does have a considerable influence, particularly at low Reynolds numbers. Because the formation of the vena contracta is an inertial effect, a decrease in the ratio of inertial to frictional forces (decrease in Reynolds number) and the corresponding change in the flow profile result in less constriction of flow at the vena contracta and an increase of the flow coefficient. In general, the sharp edge orifice plate should not be used at pipe Reynolds numbers under 2000 to 10,000 or more (Table 2.1e). The minimum recommended Reynolds number will vary from 10,000 to 15,000 for 2-in. (50-mm) through 4-in. (102-mm) pipe sizes for β ratios up to 0.5, and from 20,000 to 45,000 for higher β ratios. The Reynolds number requirement will increase with pipe size and β ratio and may range up to 200,000 for pipes 14 in. (355 mm) and larger. Maximum Reynolds numbers may be 10^6 through 4-in. (102-mm) pipe and 10^7 for larger sizes.

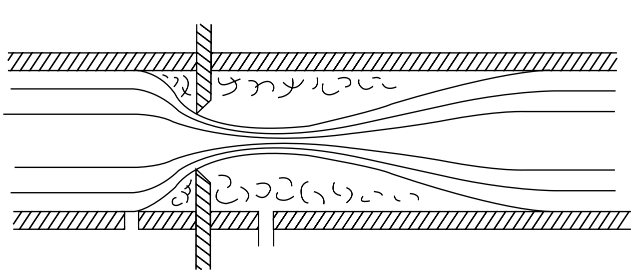


FIG. 2.15d
Flow pattern with orifice plate.

Location of Pressure Taps

For liquid flow measurement, gas or vapor accumulations in the connections between the pipe and the differential-pressure measuring device must be prevented. Pressure taps are generally located in the horizontal plane of the centerline of horizontal pipe runs. The differential-pressure measuring device is either mounted close-coupled to the pressure taps or connected through downward sloping connecting pipe of sufficient diameter to allow gas bubbles to flow up and back into the line. For gas, similar precautions to prevent accumulation of liquid are required. Taps may be installed in the top of the line, with upward sloping connections, or the differential-pressure measuring device may be close-coupled to taps in the side of the line (Figure 2.15e). For steam and similar vapors that are condensable at ambient temperatures, condensing chambers or their equivalent are generally used, usually with down-sloping connections from the side of the pipe to the measuring device. There are five common locations for the differential-pressure taps: flange taps, vena contracta taps, radius taps, full-flow or pipe taps, and corner taps.

In the United States, flange taps (Figures 2.15e and 2.15f) are predominantly used for pipe sizes 2 in. (50 mm) and larger. The manufacturer of the orifice flange set drills the taps so

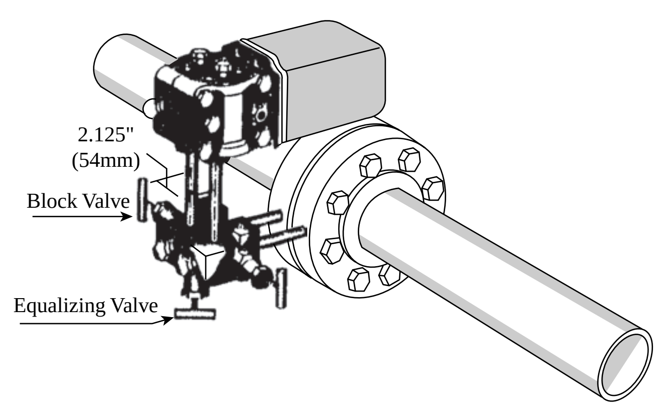


FIG. 2.15e
Measurement of gas flow with differential pressure transmitter and three-valve manifold.[3]

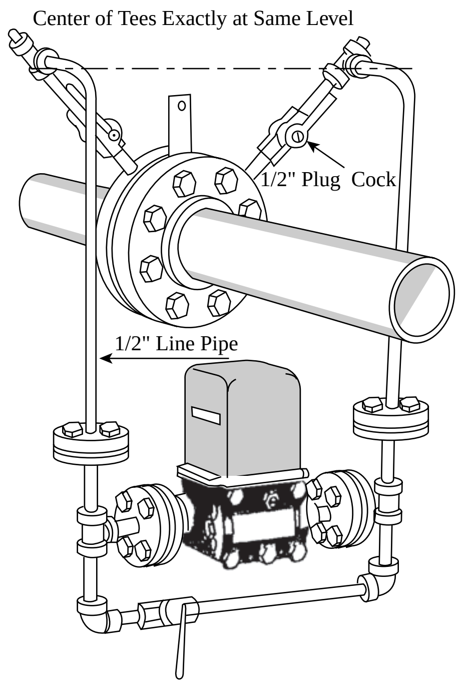


FIG 2.15f
Steam flow measurement using standard manifold.[3]

that the centerlines are 1 in. (25 mm) from the orifice plate surface. This location also facilities inspection and cleanup of burrs, weld metal, and so on that may result from installation of a particular type of flange. Flange taps are not recommended below 2 in. (50 mm) pipe size and cannot be used below 1.5 in. (37.5 mm) pipe size, since the vena contracta may be closer than 1 in. (25 mm) from the orifice plate. Flow for a distance of several pipe diameters beyond the vena contracta tends to be unstable and is not suitable for differential-pressure measurement (Figure 2.15a).

Vena contracta taps use an upstream tap located one pipe diameter upstream of the orifice plate and a downstream tap located at the point of minimum pressure. Theoretically, this is the optimal location. However, the location of the vena contracta varies with the orifice-to-pipe diameter ratio and is thus subject to error if the orifice plate is changed. A tap location too far downstream in the unstable area may result in inconsistent measurement. For moderate and small pipe, the location of the vena contracta is likely to lie at the edge of or under the flange. It is not considered good piping practice to use the hub of the flange to make a pressure tap. For this reason, vena contracta taps are normally limited to pipe sizes 6 in. (152 mm) or larger, depending on the flange rating and dimensions.

Radius taps are similar to vena contracta taps except that the downstream tap is located at one-half pipe diameter (one radius) from the orifice plate. This practically assures that the tap will not be in the unstable region, regardless of orifice diameter. Radius taps today are generally considered superior to the vena contracta tap, because they simplify the pressure

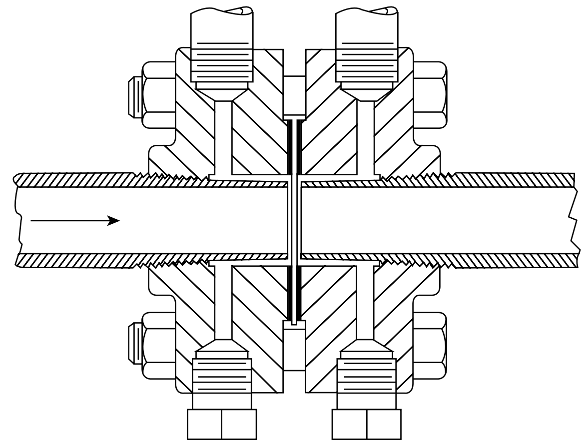


FIG 2.15g
Corner tap installation.

tap location dimensions and do not vary with changes in orifice β ratio. The same pipe size limitations apply as to the vena contracta tap.

Pipe taps are located 2.5 pipe diameters upstream and 8 diameters downstream from the orifice plate. Because of the distance from the orifice, exact location is not critical, but the effects of pipe roughness, dimensional inconsistencies, and so on are more severe. Uncertainty of measurement is perhaps 50% greater with pipe taps than with taps close to the orifice plate. These taps are normally used only where it is necessary to install an orifice meter in an existing pipeline and radius or where vena contracta taps cannot be used.

Corner taps (Figure 2.15g) are similar in many respects to flange taps, except that the pressure is measured at the "corner" between the orifice plate and the pipe wall. Corner taps are very common for all pipe sizes in Europe, where relatively small clearances exist in all pipe sizes. The relatively small clearances of the passages constitute possible sources of trouble. Also, some tests have indicated inconsistencies with high β ratio installations, attributed to a region of flow instability at the upstream face of the orifice. For this situation, an upstream tap one pipe diameter upstream of the orifice plate has been used. Corner taps are used in the United States primarily for pipe diameters of less than 2 in. (50 mm).

ECCENTRIC AND SEGMENTAL ORIFICE PLATES

The use of eccentric and segmental orifices is recommended where horizontal meter runs are required and the fluids contain extraneous matter to a degree that the concentric orifice would plug up. It is preferable to use concentric orifices in a vertical meter tube if at all possible. Flow coefficient data is limited for these orifices, and they are likely to be less accurate. In the absence of specific data, concentric orifice data may be applied as long as accuracy is of no major concern.

The eccentric orifice plate, Figure 2.15h, is like the concentric plate except for the offset hole. The segmental orifice

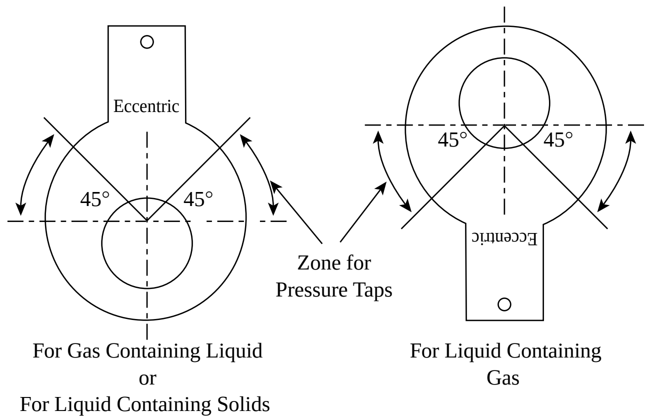


FIG. 2.15h
Eccentric orifice plate.

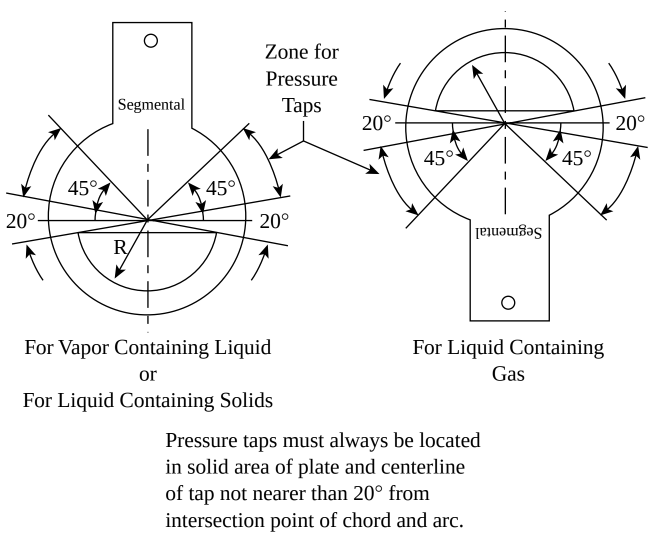


FIG. 2.15i
Segmental orifice plate.

plate, Figure 2.15i, has a hole that is a segment of a circle. Both types of plates may have the hole bored tangent to the inside wall of the pipe or more commonly tangent to a concentric circle with a diameter no smaller than 98% of the pipe internal diameter. The segmental plate is parallel to the pipe wall. Care must be taken so that no portion of the flange or gasket interferes with the hole on either type plate. The equivalent β for a segmental orifice may be expressed as $\beta = \sqrt{a/A}$, where a is the area of the hole segment, and A is the internal pipe area.

In general, the minimum line size for these plates is 4 in. (102 mm). However, the eccentric plate can be made in smaller sizes as long as the hole size does not require beveling. Maximum line sizes are unlimited and contingent only on calculation data availability. Beta ratio limits are limited to between 0.3 and 0.8. Lower Reynolds number limit is 2000D (D in inches) but not less than 10,000. For compressible fluids, $\Delta P/P_1 \leq 0.30$, where ΔP and P_1 are in the same units.

Flange taps are recommended for both types of orifices, but vena contracta taps can be used in larger pipe sizes. The taps for the eccentric orifice should be located in the quadrants directly opposite the hole. The taps for the segmental orifice should always be in line with the maximum dam height. The straight edge of the dam may be beveled if necessary using the same criteria as for a square edge orifice. To avoid confusion after installation, the tabs on these plates should be clearly stamped "eccentric" or "segmental."

QUADRANT EDGE AND CONICAL ENTRANCE ORIFICE PLATES

The use of quadrant edge and conical entrance orifice plates is limited to lower pipe Reynolds numbers where flow coefficients for sharp-edged orifice plates are highly variable, in the range of 500 to 10,000. With these special plates, the stability of the flow coefficient increases by a factor of 10. The minimum allowable Reynolds number is a function of β ratio, and the allowable β ratio ranges are limited. Refer to Table 2.15j for β ratio range and minimum allowable Reynolds number. The maximum allowable pipe Reynolds number ranges from 500,000 × (β – 0.1) for quadrant edge to 200,000 × (β) for the conical entrance plate. The conical entrance also has a minimum $D \geq 0.25$ in. (6.35 mm). For compressible fluids, $\Delta P/P_1 \leq 0.25$ where ΔP and P_1 are in the same units

Flange pressure taps are preferred for the quadrant edge, but corner and radius taps can also be used with the same flow coefficients. For the conical entrance units, reliable data

TABLE 2.15j
Minimum Allowable Reynolds Numbers for Conical and Quadrant Edge Orifices

Type		*Re Limits*										
Conical entrance	β	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	
	Re	25	28	30	33	35	38	40	43	45	48	
	β	0.20	0.21	0.22	0.23	0.24	0.25	0.26	0.27	0.28	0.29	0.30
	Re	50	53	55	58	60	63	65	68	70	73	75
Quadrant edge	β	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60			
	Re	250	300	400	500	700	1000	1700	3300			

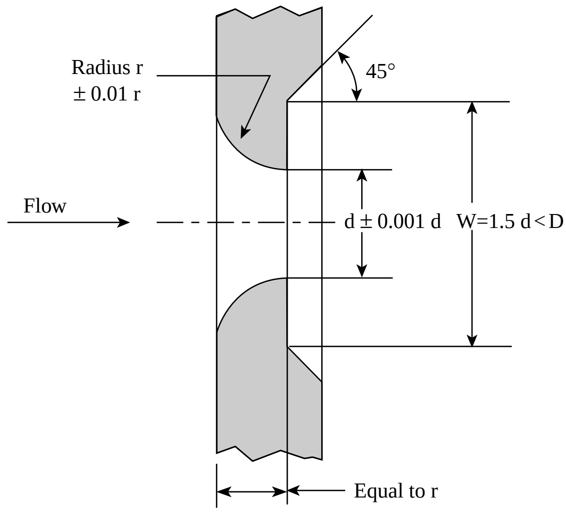


FIG. 2.15k
Quadrant edge orifice plate.

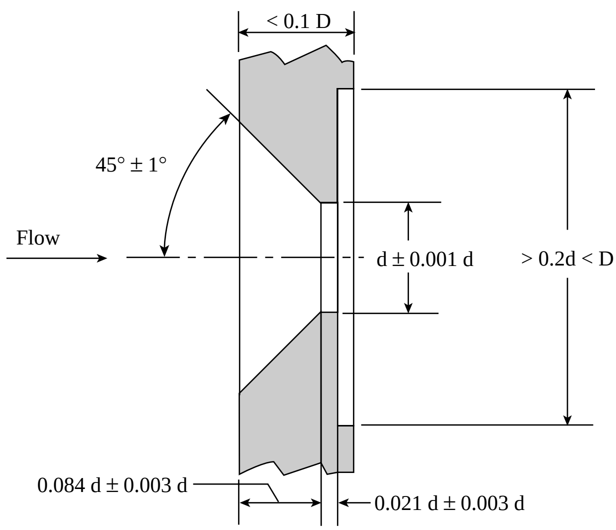


FIG. 2.15l
Conical entrance orifice plate.

is available for corner taps only. A typical quadrant edge plate is shown in Figure 2.15k, and a typical conical entrance orifice plate is shown in Figure 2.15l. These plates are thicker and heavier than the normal sharp-edge type. Because of the critical dimensions and shape, the quadrant edge is difficult to manufacture; it is recommended that it be purchased from skilled commercial fabricators. The conical entrance is much easier to make and could be made by any qualified machine shop. While these special orifice forms are very useful for lower Reynolds numbers, it is recommended that, for a pipe Re > 100,000, the standard sharp-edge orifice be used. To avoid confusion after installation, the tabs on these plates should be clearly stamped "quadrant" or "conical."

An application summary of the different orifice plates is given in Table 2.15m. For dirty gas service, the annular orifice plate (Figure 2.24a) can also be considered.

TABLE 2.15m
Selecting the Right Orifice Plate for a Particular Application

Orifice Type	*Appropriate Process Fluid*	*Reynolds Number Range*	*Normal Pipe Sizes, in. (mm)*
Concentric, square edge	Clean gas and liquid	Over 2000	0.5 to 60 (13 to 1500)
Concentric, quadrant, or conical edge	Viscous clean liquid	200 to 10,000	1 to 6 (25 to 150)
Eccentric or segmental square edge	Dirty gas or liquid	Over 10,000	4 to 14 (100 to 350)

THE INTEGRAL ORIFICE

Miniature flow restrictors provide a convenient primary element for the measurement of small fluid flows. They combine a plate with a small hole to restrict flow, its mounting and connections, and a differential-pressure sensor—usually a pneumatic or electronic transmitter. Units of this type are often referred to as *integral orifice* flowmeters. Interchangeable flow restrictors are available to cover a wide range of flows. A common minimum standard size is a 0.020-in. (0.5-mm) throat diameter, which will measure water flow down to 0.0013 GPM (5 cm^3/min) or airflow at atmospheric pressure down to 0.0048 SCFH (135 cm^3/min) (Figure 2.15n).

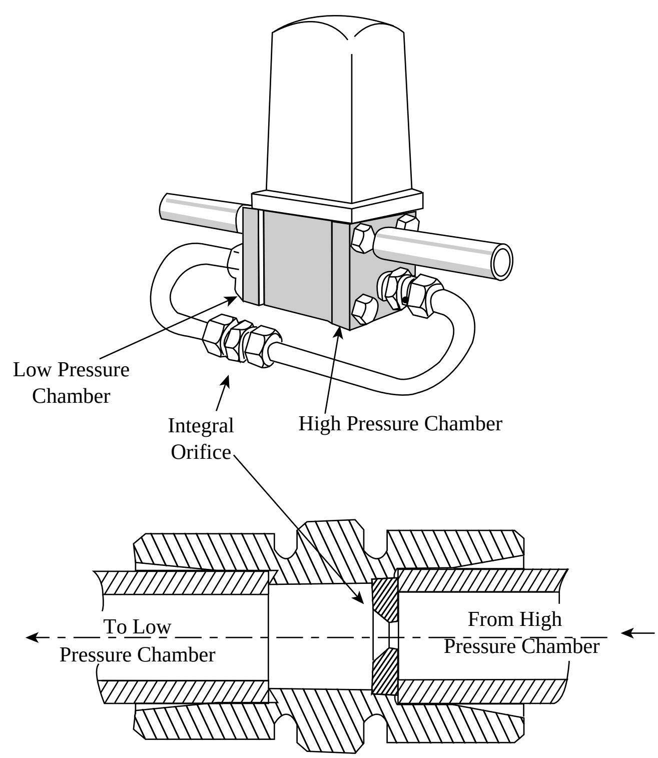


FIG. 2.15n
Typical integral orifice meter.

Miniature flow restrictors are used in laboratory-scale processes and pilot plants, to measure additives to major flow streams, and for other small flow measurements. Clean fluid is required, particularly for the smaller sizes, not only to avoid plugging of the small orifice opening but because a buildup of even a very thin layer on the surface of the element will cause an error.

There is little published data on the performance of these small restrictors. These are proprietary products with performance data provided by the supplier. Where accuracy is important, direct flow calibration is recommended. Water flow calibration, using tap water, a soap watch, and a glass graduate (or a pail and scale) to measure total flow, is readily carried out in the instrument shop or laboratory. For viscous liquids, calibration with the working fluid is preferable, because viscosity has a substantial effect on most units. Calibration across the working range is recommended, given that precise conformity to the square law may not exist. Some suppliers are prepared to provide calibrated units for an added fee.

INSTALLATION

The orifice is usually mounted between a pair of flanges. Care should be exercised when installing the orifice plate to be sure that the gaskets are trimmed and installed such that they do not protrude across the face of the orifice plate beyond the inside pipe wall (Figure 2.15o). A variety of special devices are commercially available for mounting orifice plates, including units that allow the orifice plate to be inserted and removed from a flowline without interrupting the flow (Figure 2.15p). Such manually operated or motorized orifice fittings can also be used to change the

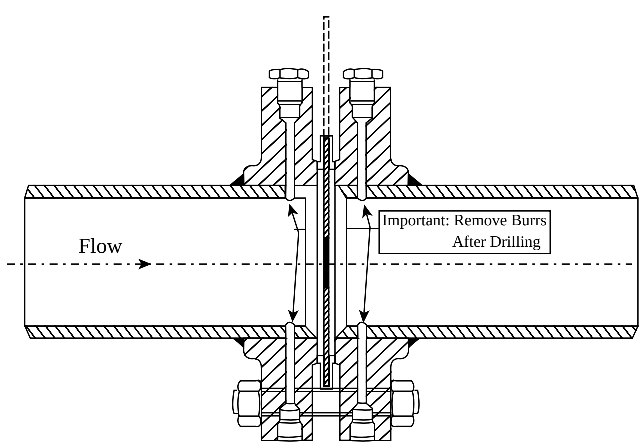
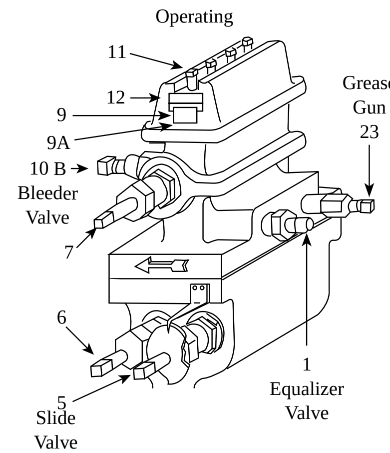


FIG. 2.15o
Prefabricated meter run with inside surface of the pipe machined for smoothness after welding for a distance of two diameters from each flange face. The mean pipe ID is averaged from four measurements made at different points. They must not differ by more than 0.3%.[3]

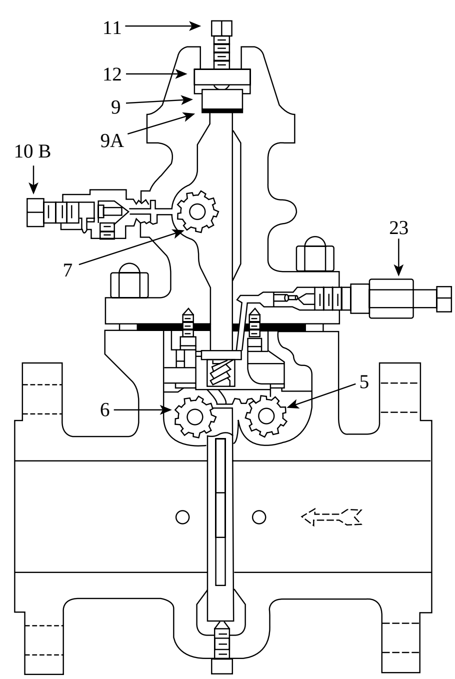


To Remove Orifice Plate

(A) Open No. 1 (Max. Two Turns Only)
(B) Open No. 5
(C) Rotate No. 6
(D) Rotate No. 7
(E) Close No. 5
(F) Close No. 1
(G) Open No. 10 B
(H) Lubricate thru No. 23
(I) Loosen No. 11 (do not remove No. 12)
(J) Rotate No. 7 to free Nos. 9 and 9A
(K) Remove Nos. 12, 9, and 9A

To Replace Orifice Plate

(A) Close 10 B
(B) Rotate No. 7 Slowly Until Plate Carrier is Clear of Sealing Bar and Gasket Level. Do Not Lower Plate Carrier onto Slide Valve.
(C) Replace Nos. 9A, 9, and 12
(D) Tighten No. 11
(E) Open No. 1
(F) Open No. 5
(G) Rotate No. 7
(H) Rotate No. 6
(I) Close No. 5
(J) Close No. 1
(K) Open 10 B
(L) Lubricate thru No. 23
(B) Close No. 10 B



Side Sectional Elevation

FIG. 2.15p
Typical orifice fitting. (Courtesy of Daniel Measurement and Control.)

flow range by sliding a different orifice opening into the flowing stream.

To avoid errors resulting from disturbance of the flow pattern due to valves, fittings, and so forth, a straight run of smooth pipe before and after the orifice is recommended. Required length depends on β ratio (ratio of the diameter of the orifice to inside diameter of the pipe) and the severity of the flow disturbance.

For example, an upstream distance to the orifice plate of 45 pipe diameters with 0.75 β ratio is the minimum recommendation for a throttling valve. For a single elbow at the same β, the minimum distance would be only 17 pipe diameters. Figure 2.15q gives minimum values for a variety of upstream disturbances. Upstream lengths greater than the minimum are recommended. A downstream pipe run of five pipe diameters from the orifice plate is recommended in all cases. This straight run should not be interrupted by thermowells or other devices inserted into the pipe.

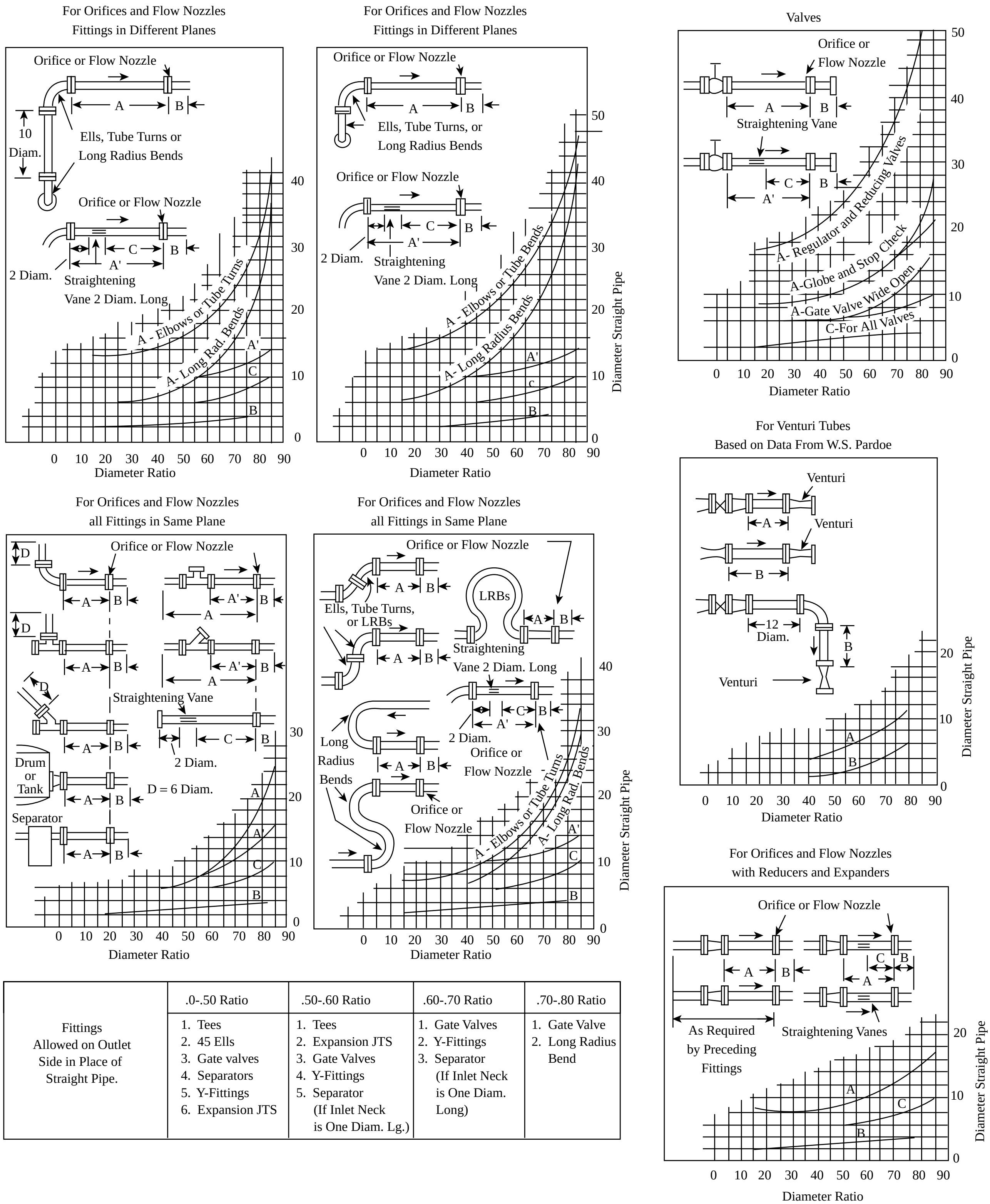
Where it is not practical to install the orifice in a straight run of the desired length, the use of a straightening vane to eliminate swirls or vortices is recommended. Straightening vanes are manufactured in various configurations (Figure 2.15r) and are available from commercial meter tube fabricators. They should be installed so that there are at least two pipe diameters between the disturbance source and vane entry and at least six pipe diameters from the vane exit to the upstream high pressure tap of the orifice.

The installation of the pressure taps is important. Burrs and protrusions at the tap entry point must be removed. (Figure 2.15o). The tap hole should enter the line at a right angle to the inside pipe wall and should be slightly beveled. Considerable error can result from protrusions that react with the flow and generate spurious differential pressure. Careful installation is particularly important when full-flow taps are located in areas of full pipe velocity and in positions that are difficult to inspect.

LIMITATIONS

Certain limitations exist in the application of the concentric, sharp-edged orifice.

1. The concentric orifice plate is not recommended for slurries and dirty fluids, where solids may accumulate near the orifice plate (Table 2.15m).
2. The sharp-edged orifice plate is not recommended for strongly erosive or corrosive fluids, which tend to round over the sharp edge. Orifice plates made of materials that resist erosion or corrosion are used for conditions that are not too severe.
3. For flows at less than 10,000 Reynolds number (determined in the pipe), the correction factor for Reynolds number may introduce problems in determining the total flow when the flow rate varies considerably (Figure 2.15b). The quadrant-edged orifice plate is recommended for this application in preference to the sharp-edged plate (Table 2.15m).
4. For liquids with entrained gas or vapor, a "vent hole" in the plate can be used for horizontal meter runs to prevent accumulation of gas ahead of the orifice plate (Figure 2.15c). If the diameter of the vent hole is less than 10% of the orifice diameter, then the flow is less than 1% of the total flow. If this error cannot be tolerated, appropriate correction can be made to the orifice calculation. On dirty service, vent or drain holes are considered to be of little value, because they are subject to plugging; they are not recommended.
5. In a similar fashion, a drain or weep hole can be provided for gas with entrained liquid. However, it is recommended that meters for liquid with entrained gas or gas with entrained liquid services be installed vertically. Normally, the flow direction would be upward for liquids and downward for gases. For severe entrainment situations, eccentric or segmental orifice plates should be used.
6. The basic flow equations are based on flow velocities well below sonic. Orifice measurement is also used for flows approaching sonic velocity but requires a different theoretical and computational approach.
7. For concentric orifice plates, it is recommended that the β ratio be limited to a range of 0.2 to 0.65 for best accuracy. In exceptional cases, this can be extended to a range of 0.15 to 0.75.
8. For large flows, the pressure loss through an orifice can result in significant cost in terms of power requirements (see Section 2.1). Venturi tubes with relatively large pressure recovery substantially decrease the pressure loss. Lo-Loss Tubes, Dall Tubes, Foster Flow Tubes, and similar proprietary primary elements develop 95% or better pressure recovery. The pressure loss is less than 5% of differential pressure (see Figure 2.29f). Elbow taps involve no added pressure loss (see Section 2.6). Pitot tube elements introduce negligible loss. Orifice plates can be sized for full-scale differential pressure ranging from 5 in. (127 mm) of water to several hundred inches of water. Most commonly the range is from 20 to 200 in. (508 to 5080 mm) of water. The pressure recovery ratio of an orifice (except for pipe taps) can be estimated by $(1 - \beta^2)$.
9. For compressible fluids, $\Delta P/P_1$ should be ≤0.25 where ΔP and P_1 are in the same units. This will minimize the errors and corrections required for density changes in flow through the orifice.
10. The use of vent and drain holes is discouraged, if in order to keep them from plugging, they would need to be large enough to adversely affect accuracy.



Fittings Allowed on Outlet Side in Place of Straight Pipe.	.0-.50 Ratio	.50-.60 Ratio	.60-.70 Ratio	.70-.80 Ratio
	1. Tees 2. 45 Ells 3. Gate valves 4. Separators 5. Y-Fittings 6. Expansion JTS	1. Tees 2. Expansion JTS 3. Gate Valves 4. Y-Fittings 5. Separator (If Inlet Neck is One Diam. Lg.)	1. Gate Valves 2. Y-Fittings 3. Separator (If Inlet Neck is One Diam. Long)	1. Gate Valve 2. Long Radius Bend

FIG. 2.15q
Orifice straight-run requirements. (Reprinted courtesy of The American Society of Mechanical Engineers.)

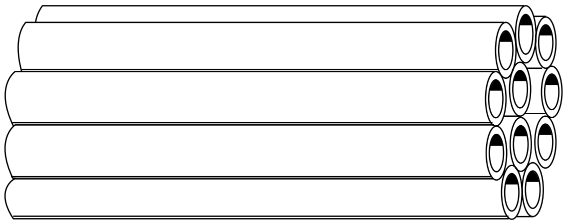


FIG 2.15r
Straightening vane.

ORIFICE BORE CALCULATIONS

Accurate flow calibration, traceable to recognized standards and using the working fluid under service conditions, is difficult and expensive. For large gas flows, it is nearly impossible and is rarely done. A major advantage of orifice metering is the ease with which flow can be accurately determined from a few simple, readily available measurements. In particular, for the concentric, sharp-edged orifice, measurement confidence is supported by a large body of experience and precise, painstaking tests.

Precise flow calculations are quite complex, although the calculation methods and equations have been well standardized. These calculation methods are thoroughly covered in the references at the end of this section. Most, if not all, of the calculations have been automated using readily available computer software for both volumetric and mass flow calculations.

The Old Approach

Before the proliferation of computers, approximate calculations were used, giving only moderate accuracy. These are illustrated below more for historical perspective than as a recommended technique. Figure 2.15s illustrates how orifice bore diameters were approximated, and Table 2.15t lists the maximum air, water, and steam flow capacities for both flange and pipe tap installations at various pressure drops. When using Figure 2.15s, the following equations were used to determine the orifice bore.

For liquid flow,

$$Z = \frac{5.663\, ER\sqrt{hG_f}}{GPM\, G_t} \qquad \textbf{2.15(5)}$$

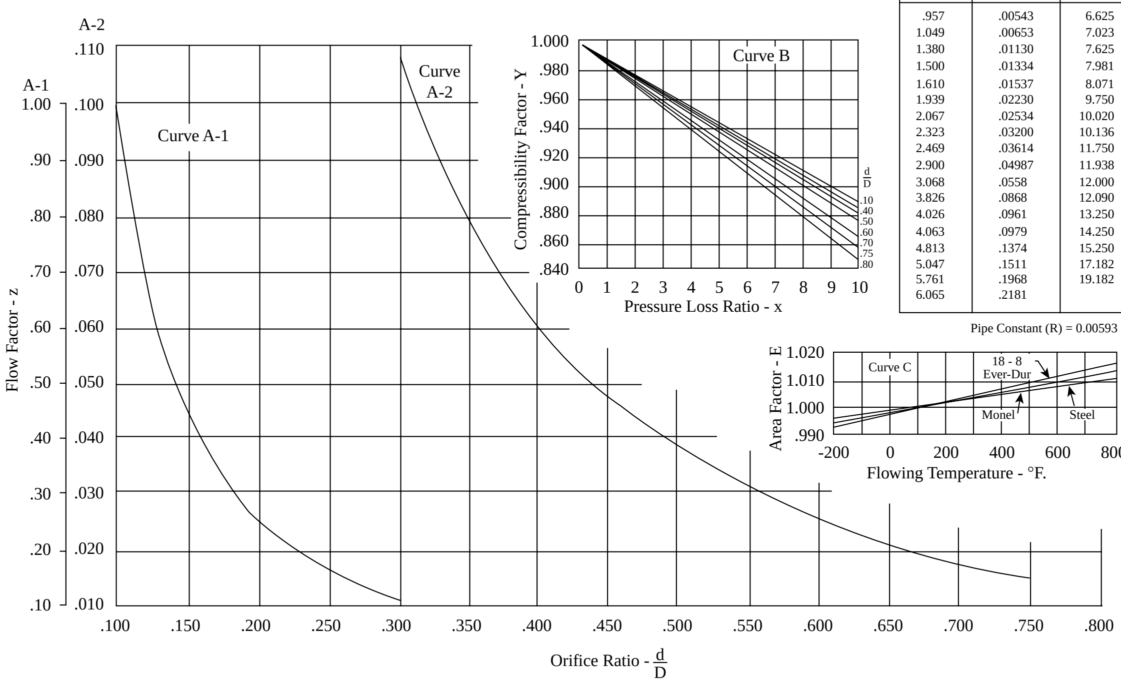
For steam,*

$$Z = \frac{358.9\, ERY}{lbm/hr}\sqrt{\frac{h}{V}} \qquad \textbf{2.15(6)}$$

For gas,*

$$Z = \frac{7727\, ERY}{SCFH}\sqrt{\frac{hP_f}{GT_f}} \qquad \textbf{2.15(7)}$$

* For steam and gas, h expressed in inches H_2O should be equal to or less than P_f expressed in PSIA units.



Pipe Constants			
Pipe I. D.	Pipe Constant	Pipe I. D.	Pipe Constant
.957	.00543	6.625	.2603
1.049	.00653	7.023	.2925
1.380	.01130	7.625	.3448
1.500	.01334	7.981	.3777
1.610	.01537	8.071	.3863
1.939	.02230	9.750	.5637
2.067	.02534	10.020	.5954
2.323	.03200	10.136	.6092
2.469	.03614	11.750	.8187
2.900	.04987	11.938	.8451
3.068	.0558	12.000	.8539
3.826	.0868	12.090	.8668
4.026	.0961	13.250	1.0411
4.063	.0979	14.250	1.2042
4.813	.1374	15.250	1.3791
5.047	.1511	17.182	1.7507
5.761	.1968	19.182	2.1819
6.065	.2181		

Pipe Constant (R) = 0.00593 (I. D.)^2

FIG. 2.15s
Orifice bore determination chart (flange taps). © 1946 by Taylor Instrument Companies. (ABB Kent-Taylor Inc.)

TABLE 2.15t
*Orifice Flowmeter Capacity Table**

Pipe Size	Actual Inside Diam. (I.D.) Sched. 40	Maximum Orifice Diam.	Meter Range	Flange and Vena Contracta Taps — Liquid: Water (SG = 1)	Flange and Vena Contracta Taps — Steam: 100 PSIG Saturated	Flange and Vena Contracta Taps — Gas: Air (SG = 1.0) @ 100 PSIG and 60°F	Pipe Taps — Liquid: Water (SG = 1)	Pipe Taps — Steam: 100 PSIG Saturated	Pipe Taps — Gas: Air (SG = 1.0) @ 100 PSIG and 60°F
Inches	Inches	Inches	Inches of Water	Gal./Min.	Lb./Hr.	Std. Cu. Ft/Min.	Gal./Min.	Lb./Hr.	Std. Cu. Ft./Min.
1/2	0.622	0.435	200	10.6	338	119	15.7	506	178
			100	7.5	239	84	11.2	358	126
			50	5.3	170	59	7.9	253	89
			20	3.3	107	37	5.0	160	57
			10	2.4	76	27	3.5	113	40
			2.5	1.17	38	13	1.7	56	20
1	1.049	0.734	200	30	963	295	44.8	1440	507
			100	21.2	682	239	31.7	1017	358
			50	15.0	482	170	22.4	719	253
			20	9.5	305	108	14.2	455	160
			10	6.7	216	76	10.1	323	113
			2.5	3.35	108	38	5.0	161	56
1 1/2	1.610	1.127	200	70.7	2270	796	105	3380	1190
			100	50.1	1600	564	75	2390	844
			50	35.1	1135	399	52.7	1690	596
			20	22.4	718	253	33.4	1070	378
			10	15.8	683	178	23.6	758	267
			2.5	7.9	254	90	11.8	379	133
2	2.067	1.448	200	116	3740	1313	174	5580	1966
			100	83	2645	932	123	3950	1390
			50	58.5	1870	658	87	2790	983
			20	37.0	1183	417	55	1768	623
			10	26.1	840	295	39	1252	440
			2.5	13.1	420	148	19.4	625	220
3	3.068	2.147	200	255	8240	2905	383	12300	4330
			100	181	5830	2080	271	8700	3070
			50	128	4125	1460	191	6160	2175
			20	81.5	2610	922	121	3900	1375
			10	57.5	1843	653	86	2760	975
			2.5	28.8	915	325	43	1366	485
4	4.026	3.02	200	512	16400	5780	764	24500	8630
			100	362	11600	4090	540	17300	6100
			50	255	8170	2890	382	12200	4310
			20	162	5180	1830	242	7730	2730
			10	115	3670	1290	172	5470	1930
			2.5	57	1820	647	85	2710	965
5	5.047	3.78	200	800	25600	9050	1190	38200	13500
			100	557	18200	6410	845	27100	9560
			50	402	12900	4530	598	19200	6760
			20	253	8110	2870	378	12100	4280
			10	180	5750	2020	268	8580	3020
			2.5	90	2880	1010	134	4290	1510

TABLE 2.15t Continued
*Orifice Flowmeter Capacity Table**

				Flange and Vena Contracta Taps			Pipe Taps		
				Liquid	Steam	Gas	Liquid	Steam	Gas
Pipe Size	Actual Inside Diam. (I.D.) Sched. 40	Maximum Orifice Diam.	Meter Range	Water (SG = 1)	100 PSIG Saturated	Air (SG = 1.0) @ 100 PSIG and 60°F	Water (SG = 1)	100 PSIG Saturated	Air (SG = 1.0) @ 100 PSIG and 60°F
Inches	Inches	Inches	Inches of Water	Gal./Min.	Lb./Hr.	Std. Cu. Ft/Min.	Gal./Min.	Lb./Hr.	Std. Cu. Ft./Min.
6	6.065	4.55	200	1158	37100	13100	1730	55300	19500
			100	820	26300	9250	1223	39200	13800
			50	580	18600	6540	866	27700	9760
			20	367	11700	4140	547	17500	6180
			10	258	8310	2930	387	12400	4370
			2.5	129	4150	1460	193	6200	2180
8	7.981	5.9858	200	2000	64104	22511	2980	95709	33692
			100	1413	45320	15952	2110	67682	23853
			50	1000	32052	11285	1492	47855	16846
			20	634	20275	7156	943	30263	10674
			10	447	14386	5054	668	21468	7543
			2.5	223	7186	2534	333	10719	3772
10	10.020	7.5150	200	3150	101020	35475	4700	150825	53094
			100	2230	71481	25138	3325	106658	37589
			50	1578	50510	17785	2355	75413	26547
			20	998	31950	11277	1487	47691	16821
			10	706	22671	7964	1052	33830	11887
			2.5	352	11324	3994	525	16891	5944
12	12.000	9.0000	200	4520	145000	51300	6750	216000	76500
			100	3200	103000	36200	4775	153000	45100
			50	2270	72400	25600	3380	108000	38200
			20	1430	46000	16200	2135	68600	24200
			10	1012	32400	11500	1512	48300	17100
			2.5	507	16200	5740	757	24200	8560
14	13.126	9.8445	200	5415	173398	60891	8060	258887	91135
			100	3830	122588	43148	5720	183076	64520
			50	2710	86699	30526	4040	129443	45567
			20	1715	54842	19356	2555	81860	28873
			10	1210	38914	13670	1808	58068	20404
			2.5	603	19437	6855	900	28994	10202
16	15.000	11.2500	200	7065	226442	79518	10520	338084	119014
			100	5000	160089	56347	7460	239081	84258
			50	3535	113221	39864	5275	169042	59507
			20	2240	71619	25277	3335	106902	37705
			10	1580	50818	17852	2360	75832	26646
			2.5	788	25383	8952	1175	37865	13323
18	16.876	12.6570	200	8920	286324	100546	13320	427489	150487
			100	6330	202424	71248	9270	302305	106539
			50	4475	143162	50406	6675	213744	75243
			20	2830	90558	31962	4220	135172	47676
			10	1995	64256	22573	2985	95885	33693
			2.5	995	32095	11320	1485	47876	16847

TABLE 2.15t Continued
*Orifice Flowmeter Capacity Table**

				Flange and Vena Contracta Taps			Pipe Taps		
				Liquid	Steam	Gas	Liquid	Steam	Gas
Pipe Size	Actual Inside Diam. (I.D.) Sched. 40	Maximum Orifice Diam.	Meter Range	Water (SG = 1)	100 PSIG Saturated	Air (SG = 1.0) @ 100 PSIG and 60°F	Water (SG = 1)	100 PSIG Saturated	Air (SG = 1.0) @ 100 PSIG and 60°F
Inches	Inches	Inches	Inches of Water	Gal./Min.	Lb./Hr.	Std. Cu. Ft/Min.	Gal./Min.	Lb./Hr.	Std. Cu. Ft./Min.
20	18.814	14.1105	200	11100	356238	125097	16550	531871	187232
			100	7870	251352	88645	11720	376121	132554
			50	5565	178119	62714	8310	265936	93616
			20	3520	112671	39766	5250	168177	59318
			10	2485	79946	28085	3715	119298	41920
			2.5	1240	39932	14084	1850	59566	20960
24	22.626	16.9695	200	16060	515222	180927	23950	769238	270791
			100	11375	364250	128206	16960	543978	191710
			50	8035	257611	90703	12000	384619	135395
			20	5090	162954	57513	7585	243233	85790
			10	3590	115625	40619	5375	172539	60628
			2.5	1795	57753	20369	2675	86150	30314

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where
E = area factor, determined from curve C on Figure 2.15s
R = pipe constant, determined from table on Figure 2.15s
G = specific gravity of gas (air = 1.0)
G_f = specific gravity of liquid at operating temperature
G_t = specific gravity of liquid at 60°F (15.6°C)
h = pressure differential across orifice in inches H_2O
Y = compressibility factor, determined from curve B in Figure 2.15s
V = specific volume (ft^3/lbm), determined from steam tables provided in the Appendix
T_f = flowing temperature expressed in °R (°F +460)
P_f = flowing pressure in PSIA
X = pressure loss ratio defined as $h/2P_f$

A useful simplified form of the mass flow equation [Equation 2.15(3)] is

$$W = 359\ Cd^2 \sqrt{\frac{h\rho}{1-\beta^4}} \tag{2.15(8)}$$

where
W = mass flow in lb/h
d = orifice diameter in inches
h = differential pressure in inches of water; water density assumed to be 62.32 lb/ft^3, corresponding to 68°F (20°C)
ρ = operating density in lb/ft^3
β = ratio of orifice diameter to pipe diameter in pure number
C = coefficient of discharge in pure number

This is a modification of the basic equation for mass flow [Equation 2.15(3)] substituting the 359 $Cd^2\sqrt{1-\beta^4}$ for kA. The constant 359 includes a factor for the chosen units of measurement. The coefficient of discharge is involved with the flow pattern established by the orifice, including the vena contracta and its relation to the differential-pressure measurement taps. An average value of $C = 0.607$ can be used for flange and other close-up taps, which gives working equation

$$W = 218d^2 \sqrt{\frac{h\rho}{1-\beta^4}} \tag{2.15(9)}$$

For full flow taps, $C = 0.715$, and the equation becomes

$$W = 275d^2 \sqrt{\frac{h\rho}{1-\beta^4}} \tag{2.15(10)}$$

These working equations can be used for approximate calculations of the flow of liquids, vapors, and gases through any type of sharp-edged orifice. When using orifices for measurement in weight units, errors in determination of ρ must be considered. (Refer to Chapter 6 for density measurement and sensors.) Accurate determination of density under flowing conditions is difficult, particularly for gases and vapors. In some cases, even liquids are subject to density changes with both temperature *and* pressure (for example, pure water in high-pressure boiler feedwater measurement).

For W, d, h, and ρ given in dimensions other than those stated, simple conversion factors apply. Transfer of ρ in Equations 2.15(8) through 2.15(10) from the numerator to denominator will give volume flow in actual cubic feet per hour at flowing conditions [see Equations 2.15(2) and 2.15(3)].

Beta ratio, and hence orifice diameter, can be calculated from a transposed form of the mass flow Equation 2.15(8).

ORIFICE ACCURACY

If the purpose of flow measurement is not absolute accuracy but only repeatable performance, then the accuracy in calculating the bore diameter is not critical, and approximate calculations will suffice. On the other hand, if the measurement is going to be the basis for the sale of, for example, valuable fluids or of large quantities of natural gas transported in high-pressure gas lines, absolute accuracy is essential, and precision in the bore calculations is critical.

Some engineers believe that, instead of individually sizing each orifice plate, bore diameters should be standardized.[6] This approach would make it practical to keep spare orifices on hand in all standard sizes. This approach seems reasonable, because the introduction of the microprocessor-based DCS systems means it is no longer important to have round figures for the full-scale flow ranges. If this approach to orifice sizing were adopted, the orifice bore diameters and d/p cell ranges would be standardized, round values, and the corresponding maximum flow would be an uneven number that corresponds to them.

If orifice bore diameters are selected from standardized sizes, the actual bore diameter required can be calculated, as is normally done, and the next size from the standard sizes (available in 0.125-in. diameter increments) can be selected. The use of this approach is practical and, although it results in an "oddball" full flow value, that is no problem for our computing equipment.

In the past, to increase flow rangeability, the natural gas pipeline transport stations used a number of parallel runs (Figure 2.15u). In these systems, the flow rangeability of the individual orifices was minimized by opening up another parallel path if the flow exceeded about 90% of full-scale flow (of the active paths) or by closing down a path when the flow in the active paths dropped to a selected low limit, such as 80%. By so limiting the rangeability, metering accuracy was kept high, but at the substantial investment of adding piping, metering hardware, and logic controls for the opening and closing of runs.

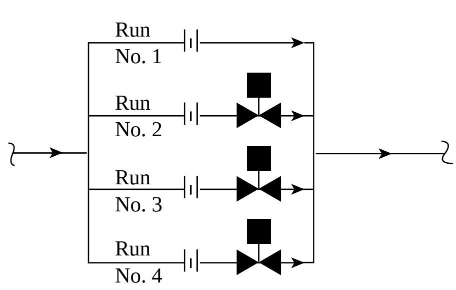

FIG. 2.15u
Metering accuracy can be maximized by keeping the flow through the active runs between 80% and 90% of full scale.[8]

Another, less expensive, choice was to use two (or more) transmitters, one for high (10 to 100%) pressure drop and the other for low (1 to 10%), and to switch their outputs depending on the actual flow. This doubled the transmitter hardware cost and added some logic expense at the receiver, but it increased the rangeability of orifice flowmeters to about 10:1.

As smart d/p transmitters with 0.1% of span error became available, another relatively inexpensive option became obtainable: the dual-span transmitter. Some smart d/p transmitters are currently available with 0.1% of span accuracy, and their spans can be automatically switched by the DCS system, based on the value of measurement.[7] Therefore, a 100:1 pressure differential range (10:1 flow range) can be obtained by automatically switching between a high (10 to 100%) and a low (1 to 10%) pressure differential span. As the transmitter accuracy at both the high and low flow condition is *0.1% of the actual span*, the overall result can be a 1% of actual flow accuracy over a 10:1 flow range.

Where the ultimate in accuracy is required, actual flow calibration of the meter run (the orifice, assembled with the upstream and downstream pipe, including straightening vanes, if any) is recommended. Facilities are available for very accurate weighed water calibrations, in lines up to 24 in. (61 cm) diameter and larger, and with a wide range of Reynolds numbers. For orifice meters, highly reliable data exists for accurate transfer of coefficient values for liquid, vapor, and gas measurement.

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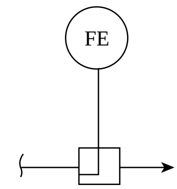
2.16 Pitot Tubes and Area Averaging Units

W. H. HOWE (1969) **J. O. HOUGHEN** (1982)
B. G. LIPTÁK, M. PTÁCNÁK (1995) **B. G. LIPTÁK** (2003)



Flow Sheet Symbol

Types	A. Standard, single-ported B. Multiple-opening, averaging C. Area averaging for ducts
Applications	Liquids, gases, and steam
Operating Pressure	Permanently installed carbon or stainless-steel units can operate at up to 1400 PSIG (97 bars) at 100°F (38°C) or 800 PSIG (55 bars) at approximately 700°F (371°C); pressure rating of retractable units is function of the ratings of the isolating value
Operating Temperature	For permanent installations, up to 750°F (399°C) in steel and up to 850°F (454°C) in stainless-steel construction
Flow Ranges	Can be used in pipes or ducts in sizes 2 in. (50 mm) or larger; no upper limit
Materials of Construction	Brass, steel, stainless steel
Minimum Reynolds Number	In the range of 20,000 to 50,000
Rangeability	Usually limited to 3:1
Straight-Run Requirements	Twenty-five to 30 pipe diameters upstream and 5 downstream are required if the pitot sensor is located downstream of a valve or of two elbows in different planes; if straightening vanes are provided, this requirement is reduced to 10 pipe diameters upstream and 5 downstream
Inaccuracy	For standard industrial units: 0.5 to 5% of full scale. Industrial pitot venturies must be individually calibrated to obtain 1% of range performance. Full-traversing pitot venturies under laboratory conditions meeting the National Bureau of Standards can limit the error to 0.5% of actual flow. Inaccuracies of individually calibrated multiple-opening averaging pitot tubes, when Reynolds numbers exceed 50,000, are 2% of range. The errors of area-averaging duct units are claimed to be between 0.5 and 2% of span. The errors listed above do not include that of the d/p cell, which is additional.
Costs	The cost of the pitot tube itself in case of a 1-in. dia. averaging tube in stainless-steel materials is $800 if fixed and $1500 if retractable for hot-tap installation. Hastelloy® units for smokestack applications can cost $2000 or more. A local pitot indicator cost $500; a d/p transmitter suited for pitot applications costs about $1,500. Calibration costs are additional and can amount to $1000/tube.
Partial List of Suppliers	ABB Automation Instrumentation (www.abb.com/us/instrumentation) (A) Air Monitor Corp. (www.airmonitor.com) (C) Alnor Instrument Co. (www.alnor.com) (A) Blue White Industries (www.bluwhite.com) (A) Brandt Instruments (www.brandt.com) (C) Dietrich Standard (www.annubar.com) (Annubar—B) Dwyer Instruments Inc. (www.dwyer-inst.com) (B)

The Foxboro Co. (www.foxboro.com) (pitot venturi—A)
Kobold Instruments Inc. (www.koboldusa.com) (B)
Meriam Instrument (www.meriam.com) (B)
Mid-West Instrument (www.midwestinstrument.com) (delta tube—B)
United Electric Controls Co. (www.ueonline.com) (A)

For the measurement of the velocities of fluids, in 1732, Henri de Pitot invented the pitot tube. Pitot tubes detect the flowing velocity at a single point (standard), at several points that lead into an averaging probe (multiported), or at many points across the cross section of a pipe or duct (area-averaging). Their advantages are low cost, low permanent pressure loss, and the capability of inserting the probe-type sensors into the process pipes while the system is under pressure (wet- or hot-tapping). The disadvantages of pitot tube-type sensors are low accuracy, low rangeability, and the limitation of being suitable only for clean liquid, gas, or vapor service unless purged.

THEORY OF OPERATION

The impact pressure on a body, which is immersed in a moving fluid is the sum of the static pressure and the dynamic pressure. Thus,

$$P_t = P + P_v \qquad \textbf{2.16(1)}$$

where
P_t = total pressure, which can be sensed by a fixed probe when the fluid at the sensing point is in an isentropic state (constant entropy)
P = static pressure of the fluid whether in motion or at rest
P_v = dynamic pressure caused by the kinetic energy of the fluid as a continuum

With respect to the energy relation at the isentropic stagnation point of an ideal probe,

$$\int_P^{P_t} \frac{dp}{\rho} = \int_o^{v_p} \frac{v_p\,dv}{g_c} \qquad \textbf{2.16(2)}$$

where
v_p = approach velocity at the probe location
ρ = fluid density
g_c = a constant

For a liquid of constant density, integration yields, at a point,

$$(P_t - P) = P_v = \frac{Pv_p^2}{2g_c} \qquad \textbf{2.16(3)}$$

For a compressible perfect gas for which $\frac{p}{\rho\gamma}$ remains constant during an isentropic change, a similar relation emerges.

$$(P_t - P) = P_v = \rho\frac{(\gamma-1)}{\gamma}\frac{v_p^2}{2g_c} \qquad \textbf{2.16(4)}$$

where γ = ratio of specific heats.

Assuming isentropic stagnation at the sensing point of the probe,

$$\int_P^{P_t} \frac{dp}{\rho} = \int_o^{v_p} \frac{V_p d^V}{g_c} \qquad \textbf{2.16(5)}$$

where, using English units,
V_p = velocity of approach, ft/s
P = pressure, lbf/ft^2
ρ = fluid density, lbm/ft^3
$g_c = 32.2 \frac{\text{lbm}}{\text{lbf}}\frac{\text{ft}}{\text{s}^2}$

If density is constant, integration yields

$$(P_t - P) = P_v = \frac{p\left(V_p^2\right)}{2g_c} \qquad \textbf{2.16(6)}$$

For a compressible perfect gas, the ratio $\frac{P}{\rho\gamma}$ remains constant during an isentropic change, and a similar relation is obtained.

$$(P_t - P) = P_v = \frac{(\gamma-1)}{\gamma}\frac{\rho\left(V_p^2\right)}{g_c} \qquad \textbf{2.16(7)}$$

where γ is the ratio of specific heats.

To compute the fluid velocity at a particular point, it is necessary to measure the values of both the static pressure

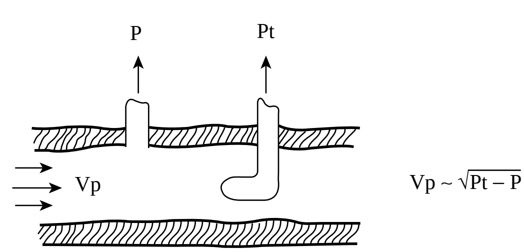


FIG. 2.16a
The velocity at a point (in the turbulent flow range) is related to the square root of the pressure difference between total and static pressures.

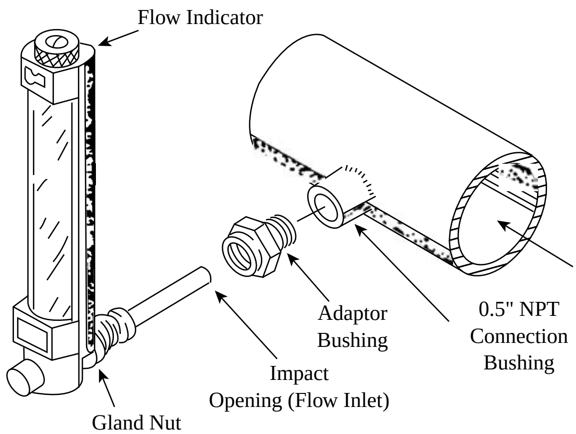


FIG. 2.16b
Pitot rotameter with bypass flow entering through impact opening (facing flow) and leaving through static port on opposite side (not shown). (Courtesy of ABB Instruments, formerly Fischer & Porter Co.)

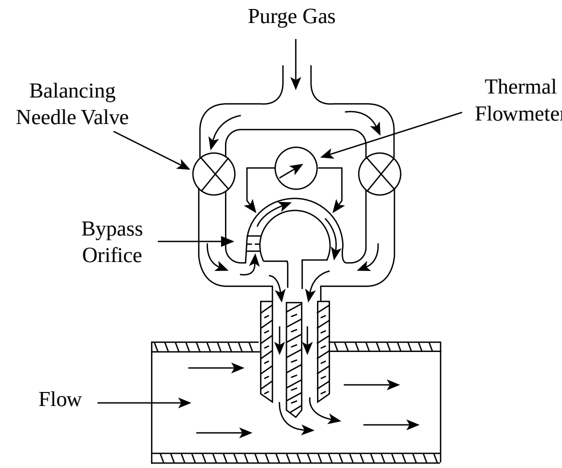


FIG. 2.16c
Pitot-tube rangeability can be increased by replacing the d/p cell detector with a thermal flowmeter.

(P) and the total pressure (P_t) at that point (Figure 2.16a), whence

$$V_P = C\frac{(P_t - P)^{0.5}}{\rho} \qquad \textbf{2.16(8)}$$

where C = a dimensional constant.

PRESSURE DIFFERENTIAL PRODUCED

One of the problems with pitot tubes is that they do not generate strong output signals. The d/p cells available are discussed in Chapter 5, under "Pressure Measurement." The minimum span of a "smart" d/p cell is 0 to 2 in. of H_2O (0 to 0.5 kPa). These smart d/p cell units are accurate up to 0.1% of actual span. For narrower differentials, down to 0 to 0.1 in. H_2O (0 to 25 Pa), the membrane-type d/p cells can be used.

In addition to using d/p cells, one can also install elastic element or manometer-type readout devices, variable-area flowmeters (Figure 2.16b), or thermal flowmeters (Figure 2.16c) as pitot tube detectors. The thermal detector gives the highest rangeability, but it can be used only if the pitot tube is purged.

STATIC PRESSURE MEASUREMENT

In process fluids flowing through pipes or ducts, the static pressure is commonly measured in one of three ways: (1) through taps in the wall, (2) by static probes inserted into the fluid stream, or (3) by small apertures located on an aerodynamic body immersed in the flowing fluid.

The data of Shaw[1] (presented by Benedict[2]) show that errors in the measurement of static pressure are minimal for velocities up to 200 ft/s (60 m/s) if the wall tap dimensions conform to those in Figure 2.16d, where the tap diameter (d) is 0.0635 in., the sensing tube ID ≅ 2d, and the tap length-to-diameter ratio (l/d) is $1.5 < l/d < 6$.

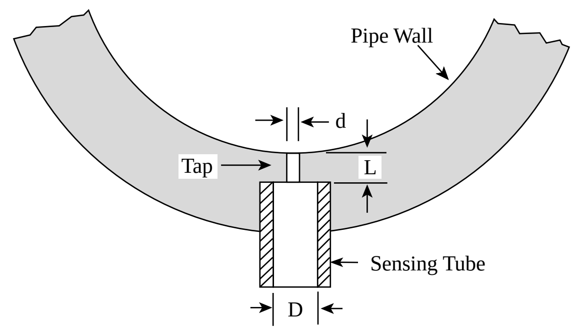


FIG. 2.16d
Wall tap for static pressure measurement.

Static pressure errors also depend on fluid viscosity, fluid velocity, and whether the fluid is compressible. Shaw[1] states that, for incompressible fluids flowing in a circular conduit with a pipe Reynolds number of 2×10^5, an error of about 1% of the mean dynamic pressure may occur using a wall tap with a diameter 1/10th that of the pipe. Rayle[3] mentions that a tap diameter of 0.03 in. (0.75 mm) with a conical countersink 0.015 in. (0.34 mm) deep will ensure nearly true static pressure sensing.

Static pressure may also be sensed through a tube inserted into the moving fluid. One configuration is shown in Figure 2.16e.

Other static probe designs are also described in the literature.[2] The aerodynamic probe is a bluff body inserted into the flowing fluid with appropriately located holes on its surface through which pressure signals are obtained. The probe is oriented so that the sensed pressure is a measure of the static pressure. Two configurations taken from Benedict,[2] the cylinder and the wedge, are shown in Figure 2.16f. The probes are rotated until the pressure sensed from each hole is the same or, alternatively, the two taps may be manifolded to obtain an averaged pressure.

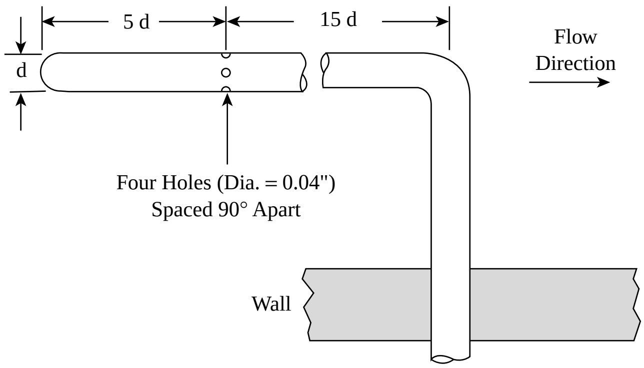


FIG. 2.16e
Typical static pressure-sensing probe.

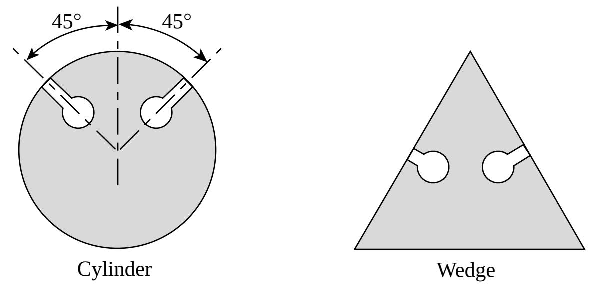


FIG. 2.16f
Two shapes of aerodynamic probes used to sense static pressure.

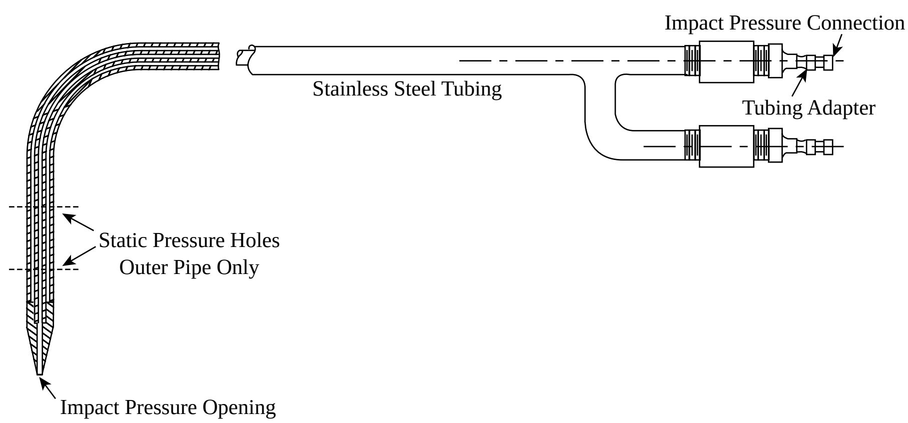


FIG. 2.16g
Typical pitot tube.

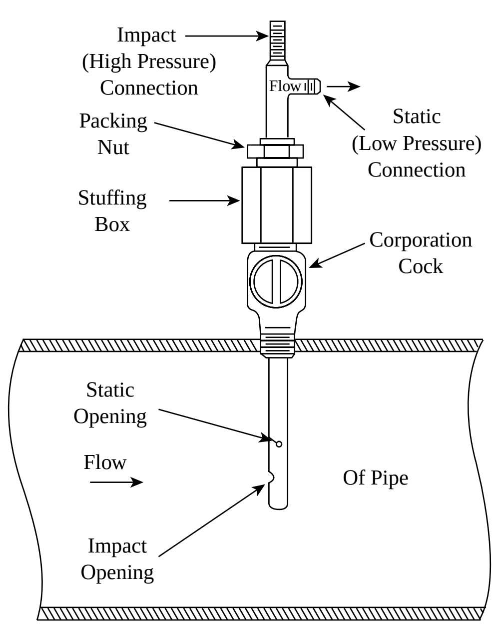


FIG. 2.16h
Schematic of an industrial device for sensing static and dynamic pressures in a flowing fluid.

The total pressure develops at the point where the flow is isentropically stagnated, which is assumed to occur at the tip of a pitot tube or at a specific point on a bluff body immersed in the stream. Figure 2.16g illustrates a typical pitot tube, also showing the taps for sensing static pressure. Another variation is shown in Figure 2.16h.

SINGLE-PORTED PITOT TUBE

Pitot tubes are sensitive to flow direction and must be carefully aligned to face into the flow. This can be difficult if the flow direction is caused to vary by changes in turbulence. The pitot tube is made less sensitive to flow direction if the impact aperture has an internal bevel of about 15° extending about 1.5 diameters into the tube. The characteristics of various designs and orientations are discussed in Benedict.[2] Figure 2.16i illustrates the typical performance of a pitot tube.

Pitot venturi and double-venturi elements have been developed to amplify the pressure signals generated by the in-stream velocity sensors, as shown in Figures 2.16j and 2.16k. These elements are intended to remain in a fixed position, so their measurements must be converted to flow rate through calibration, which accounts for the properties of

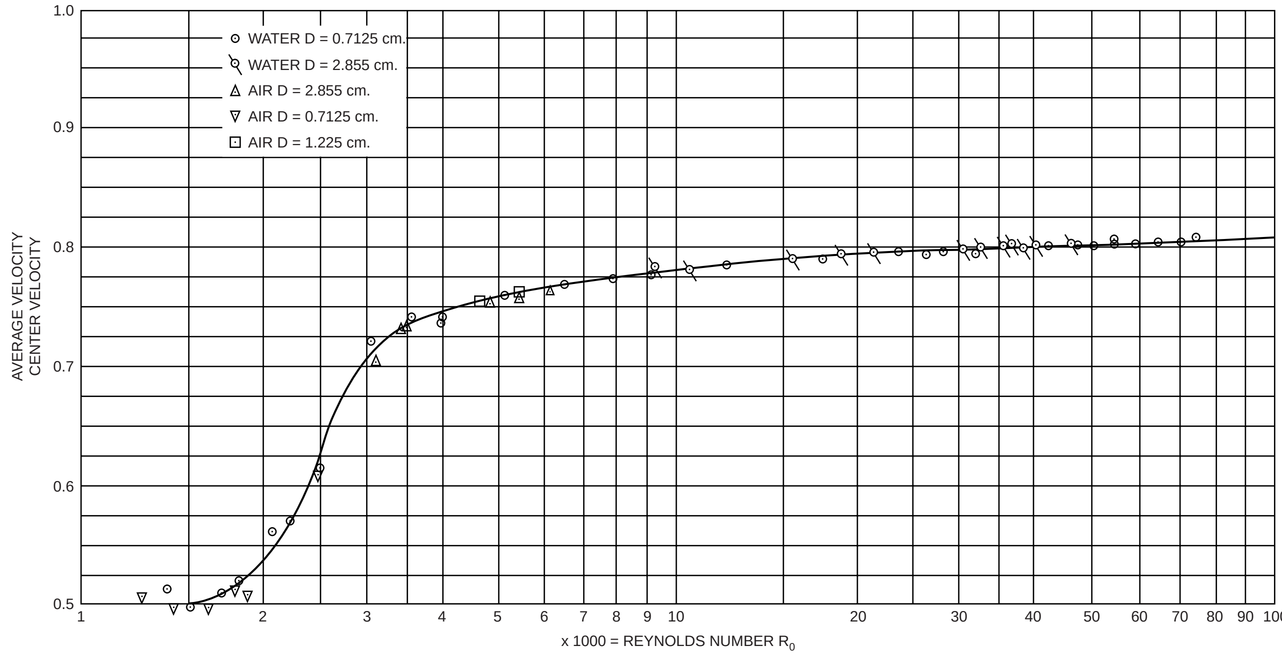


FIG. 2.16i
Center to average velocity ratios in straight and smooth pipes.[7]

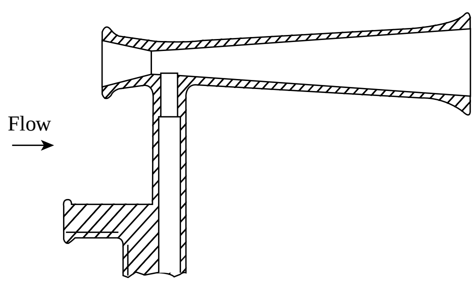


FIG. 2.16j
A pitot venturi produces a higher differential pressure than the standard pitot tube.

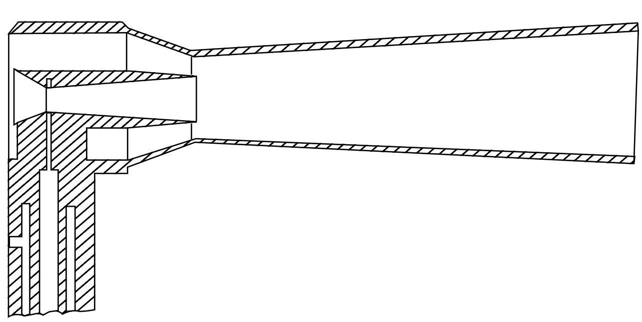


FIG. 2.16k
The double venturi produces a higher differential pressure than the standard pitot tube. (Courtesy of The Foxboro Co.)

the fluid and the velocity profile (e.g., Reynolds number). To obtain a stable velocity profile, it is recommended that a smooth, straight section of pipe, of a length equaling at least 10 to 15 pipe diameters, be provided both upstream and downstream of the probe.

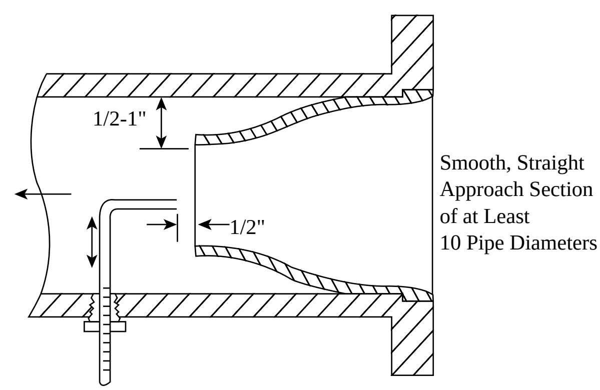


FIG. 2.16l
Reduction nozzle used to expedite velocity traverses.

To determine the average velocity in a pipe, it is necessary to traverse it with a pitot tube. For circular pipes, such an average is obtained from measurements of $(P_t - P)$ on each side of the cross section at the following locations, expressed in percentage of the diameter measured from the center:

$$\left(\sqrt{\frac{2n-1}{N}}\right)\times 100\%, \quad \left(n=1,2,3K\frac{N}{2}\right) \qquad \textbf{2.16(9)}$$

where N is the number of measurements per traverse. Two measurements normal to each other are recommended.

To improve the measurements made near the walls of pipes that are more than 6 in. (150 mm) in diameter, a reduction nozzle is inserted into the pipeline (Figure 2.16l).

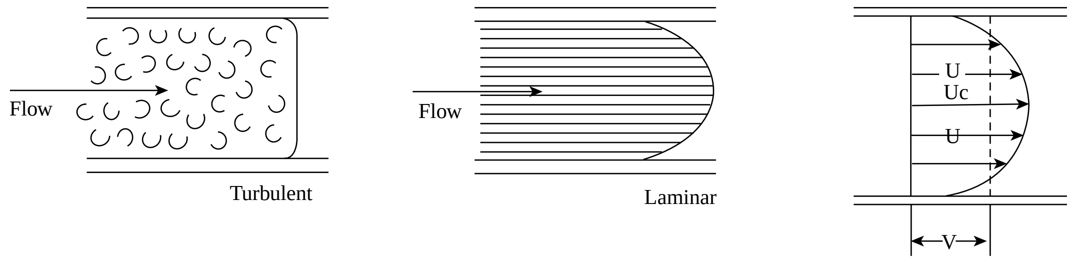


FIG. 2.16m
The velocity profile becomes flatter as the Reynolds number rises (the flow becomes more turbulent), and the task of the pitot-type flow sensor is to find the insertion depth corresponding to the average velocity (V).

Calibration of Pitot Tubes

In high-precision laboratory tests, the pitot tube is traversed across the cross-section of the pipe, thereby establishing the velocity profile that exists in the pipe. In industrial applications, the pitot tube is fixed and measures the flow velocity only at one point on the velocity profile (Figure 2.16m). If the velocity (U) measured by this fixed pitot tube is not the average velocity (V), a substantial error will result. This error cannot be easily eliminated because, even if the pitot tube insertion is carefully set to measure the average velocity V under one set of flow conditions, it will still be incorrect as soon as the flow velocity changes. At Reynolds numbers under 1000 (in the fully laminar region), the ratio between the average velocity and the center velocity is 0.5 (V/U_c = 0.5 in Figure 2.16m). In fully developed turbulent flow (Re = 50,000 or more), this same ratio is about 0.81(V/U_c = 0.8).

Unfortunately, the velocity profile is affected not only by the Reynolds number but also by the pipe surface roughness and by upstream valves, elbows, and other fittings. To reform the velocity profile, it is recommended to provide a straight pipe length of about 25 pipe diameters between the upstream disturbances and the pitot element.

If the data for calculating the Reynolds number is available, and if the pitot tube is installed in a pipe with smooth inner surface, it should be possible to design a microprocessor-based *smart pitot tube* that measures only the center velocity (U_c) and, based on that reading, accurately calculates the flow under all flow conditions.

The National Bureau of Standards calibrates pitot tubes by mounting them on a carriage, which is drawn through stagnant air at a known velocity. Smoke is introduced into the room to verify that the air is stagnant—that there is no turbulence. Such tests have shown that pitot tubes with coefficients very close to unity can be designed. Devices such as pitot-venturies or double venturies can provide flow rate measurements with less than 1% error, but only after extensive *in situ* calibration for each installation.

MULTIPLE-OPENING PITOT TUBES

One approach in attempting to overcome the inherent limitation of the pitot tube—that of being a point velocity sensor—was to measure the velocities at several points and average these readings. It was argued that, by averaging the velocities measured at four fixed points, for example (see Figure 2.16n), changes in the velocity profile will be detected, and therefore the reading of a multiple-opening pitot tube will be more accurate than that of single-point sensors.

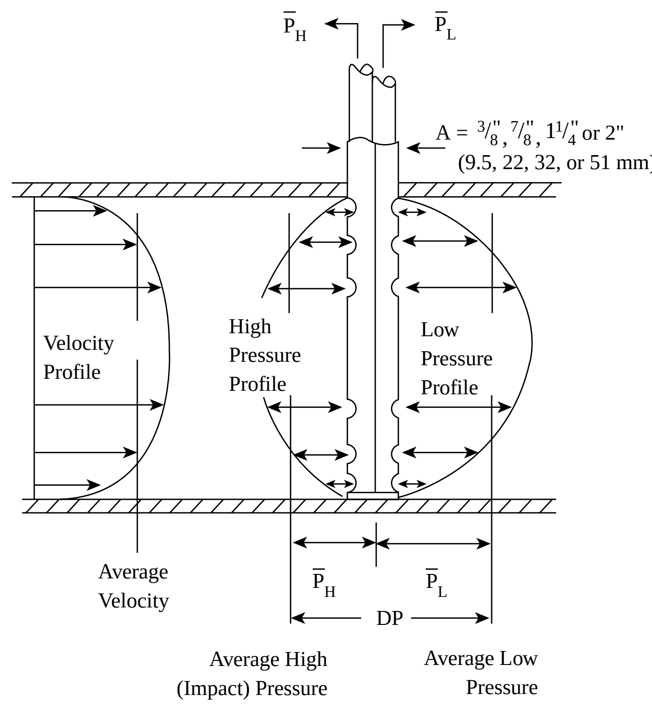


FIG. 2.16n
The design of a particular averaging pitot tube. (Courtesy of Dietrich Standard.)

The manufacturers of averaging pitot tubes usually claim that the flow coefficient (K) will stay within 2% between the Reynolds numbers of 50,000 and 1,000,000. This is probably so, but it might not be attributable to averaging action but rather to the fact that, in this highly turbulent region, the velocity profile is flat and changes very little.

Critics of this device argue that it offers little improvement over the single-opening pitot tube, because it is ineffective at Reynolds numbers below 50,000. This means that it is not applicable for the measurement of a large portion of industrial liquid flows. The other argument made by critics is that the averaging pitot tube openings are too large and, consequently, these devices are not true averaging chambers; rather, the sensed pressure is dominated by the pressure at the nearest port. For these reasons, further testing by independent laboratories is still needed.

The reason for making the ports of the averaging pitot tubes so large is to prevent plugging. Some manufacturers of area-averaging pitot tubes do overcome this limitation by purging, because the small port openings are kept clean by the purge gas, and these units can act as true averaging chambers. Naturally, they can be used only on processes in which the introduction of a purge media is acceptable.

One advantage of the averaging pitot tubes that both its manufacturers and its critics agree on is their ability to be installed into operating, pressurized pipelines. This hot-tapping capability, and the ability to remove the sensor without requiring a shutdown, are important advantages of all probe-type instruments (Figure 2.16o).

In calculating the pressure differential produced by an averaging pitot tube, one might use the equations listed in Table 2.16p. For the metric equivalents of the units used in this table, refer to the Appendix. The flow coefficient (K) of the pitot tube varies with its design. The K values of the averaging pitot tube shown in Figure 2.16n are listed in Table 2.16q. The distance "A" used in Table 2.16q is also defined in Figure 2.16n.

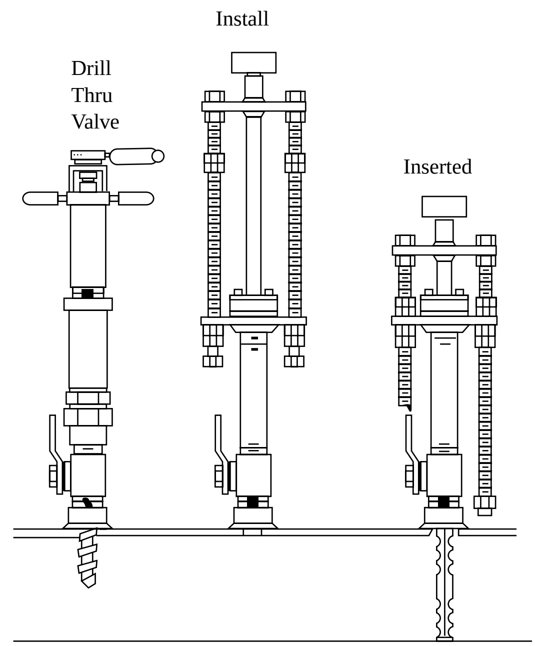


FIG. 2.16o
The hot-tap installation of an averaging pitot tube involves the same steps, which are required in installing all "retractable" probe-type instruments. (Courtesy of Dietrich Standard.)

AREA-AVERAGING PITOT STATIONS

Area-averaging pitot stations have been designed for the measurement of large flows of low-pressure gases. Measurements include the flow rate of combustion air to boilers, airflow to dryers, and air movement in HVAC systems. These units are available with circular or rectangular cross sections (Figures 2.16r and 2.16s) and can be mounted in the suction or discharge of fans or in any other large pipes or ducts. These stations are designed so that one total pressure detection port and one static pressure sensing port are located in each unit area of the cross section of the duct, and they each are

TABLE 2.16p
*Equations for Calculation of the Pressure Differential Produced by the Averaging Pitot Tube Described in Figure 2.16n**

Liquid, gas, steam (mass rate of flow) $$h_w = \left(\frac{1}{\rho_f}\right)\left(\frac{lb_m/hr}{358.94KD^2}\right)^2$$	h_w = differential pressure, inches of water at 68°F K = flow coefficient D = internal pipe diameter, inches lb_m/hr = pounds mass per hour
Liquid (volume rate of flow) $$h_w = (G_f)\left(\frac{GPM}{5.666KD^2}\right)^2$$	GPM = U.S. gallons per minute ACFH = Actual cubic feet per hour SCFH = Standard cubic feet per hour (at 14.73 psia and 60°F)
Gas (standard volumetric flow) $$h_w = \left(\frac{T_f G}{p_f}\right)\left(\frac{SCFH}{7{,}711KD^2}\right)^2$$	ρ_f = flowing density, lb_m/ft^3 for gas: $$\rho_f = \frac{p_f}{14.73} \times \frac{520}{T_f} \times .076487 \times G$$
Gas (actual volume rate of flow) $$h_w = (\rho_f)\left(\frac{ACFH}{358.94KD^2}\right)$$	.076487 lb_m/ft^3 = air density at 14.73 psia and 60°F G_f = specific gravity of liquid G = specific gravity of gas (molecular weight of air = 28.9644) T_f = temperature of flowing gas in degress Rankine (°R = °F + 460) P_f = flowing pressure, psia

* Courtesy of Dietrich Standard.

TABLE 2.16q
*The Flow Coefficient K for the Averaging Pitot Tube Shown in Figure 2.16n Having the "A" Dimension Also Defined in That Figure**

Paper Size			Flow Coefficient-K			
Size/Sch	*D-in*	*D-mm*	$A = {}^{3}/_{8}$"	$A = {}^{7}/_{8}$"	$A = 1{}^{1}/_{4}$"	$A = 2$"
2" sch 40	2.067	52.50	5912			
$2^{1}/_{2}$" sch 40	2.469	62.71	.6026			
3" sch 40	3.068	77.93	.6134			
$3^{1}/_{2}$" sch 40	3.548	90.12	.6192			
4" sch 40	4.026	102.26	.6235			
5" sch 40	5.047	128.19	.6297	.5934		
6" sch 40	6.065	154.05		.6047		
8" sch 40	7.981	202.72		.6173		
10" sch 40	10.020	254.51		.6250		
12" sch std.	12.000	304.80		.6298	.6186	
14" sch std.	13.250	336.55		.6321	.6220	
16" sch std.	15.250	387.35		.6349	.6263	
18" sch std.	17.250	438.15		.6370	.6296	
20" sch std.	19.250	488.95		.6387	.6321	
24" sch std.	23.250	590.55		.6411	.6357	.6247
30" sch std.	29.250	742.95		.6435	.6393	.6308
36" sch std.	35.250	895.35		.6450	.6416	.6346
42" sch std.	41.250	1047.7		.6461	.6432	.6373
48"	48.00	1219.20			.6445	.6395
60"	60.00	1524.0			.6461	.6422
72"	72.00	1828.80			.6472	.6439

*Courtesy of Dietrich Standard.

connected to their own manifold. The manifolds act as averaging chambers, and they are also purged to protect the sensing ports from plugging.

The straight-run requirement of these units is reduced by the addition of a hexagon-cell-type flow straightener and a flow nozzle in front of the area-averaging flow sensor. This nozzle also serves to amplify the differential pressure produced by the unit (Figure 2.16s). According to the manufacturer, this design (Figure 2.16s) reduces the straight-run requirement of most installations to a range of 0 and 10 diameters. The longest straight run (10 diameters) is recommended when the flow meter is installed downstream of a butterfly valve or a damper.

Because these area-averaging pitot stations generate very small pressure differentials, special d/p cells are required to detect these minute signals. One such detector is the membrane-type design (Fig. 2.16t), which can have a span as small as 0 to 0.01 in. H_2O (to 2.5 Pa). When such extremely small pressure differentials are detected, the pressure drop in the tubing between the d/p cell and the pitot station must

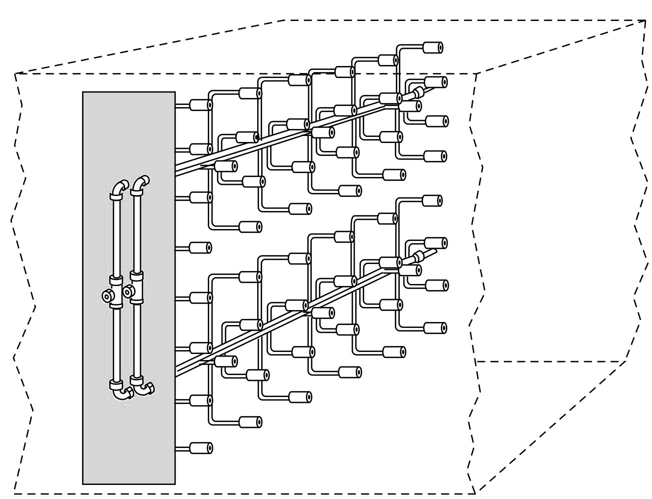


FIG. 2.16r
Installation in rectangular duct of area-averaging pitot tube ensembles for metering the flow rate of gases. (Courtesy of Air Monitor Corp.)

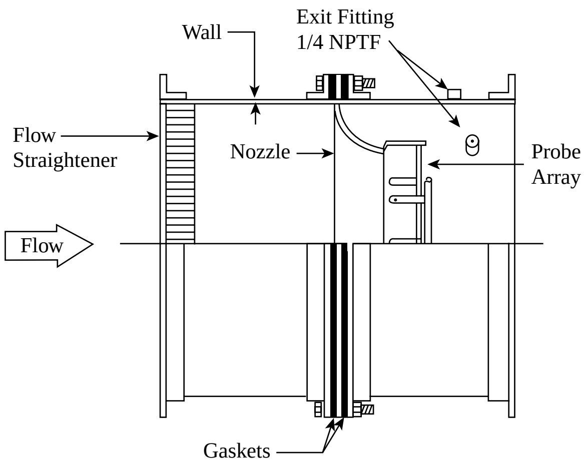


FIG. 2.16s
The flow straightener and the nozzle serve to reduce the upstream straight pipe-run requirement and increase the pressure differential generated. (Courtesy of Brandt Instruments.)

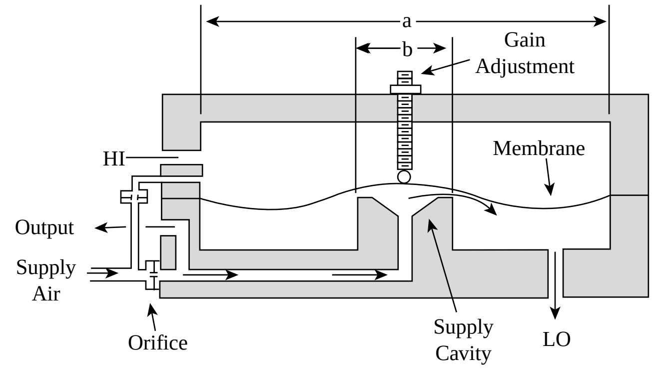


FIG. 2.16t
Membrane type d/p transmitter.

be minimized. This is achieved by making the connecting tubes short and large in diameter. The pressure differential generated by the flow element shown in Figure 2.16s can be calculated by using the equations in Table 2.16u. For the equivalent SI units for use in these equations, refer to the Appendix.

SPECIAL PITOT TUBES FOR PULSATING FLOW

The mean velocity measurements of unsteady flows, if made by conventional pitot tubes, are usually inaccurate.[4] In such measurements, one can expect errors in the range of 5 to 30% of mean total pressure. This measurement can be improved by using specially designed probes when the application involves unsteady or pulsating flows.

Figure 2.16v shows a design provided with a low-capacity capillary probe filled with silicon oil. The oil serves to transmit the process pressure to the d/p transducer. This type of probe was developed and is used by Deutsche Forschungs– und Versuchsanstalt für Luft und Raumfahrt in Germany.[5]

Figure 2.16w shows another example of a probe designed to measure unsteady flow. This probe was developed in the Aeronautical Research and Test Institute in Czechoslovakia.[6] The main design challenge in this design is to equalize the resistances in the input and output openings of the probe. Also, to protect against resonance during measurement, the natural frequency of the probe must be carefully tuned.

TABLE 2.16u
*Calculation of Pressure Differentials Generated By Area Averaging Pitot Stations**

Equations for Differential Pressure Calculation	*Terms Used*
$DP = \left(\frac{\text{ACFM}}{\text{Area}}\right)^2 \times \frac{\text{DENS}}{(1096.845)^2}$	Area = Cross-sectional area of duct section in ft^2
	ACFM = Actual cubic feet per minute
$DP = \left(\frac{\text{SCFM}}{4000.7 \times \text{Area}}\right)^2$	*DP* = Differential pressure in inches w.c.
	M = Mass flow in pounds per hour
$DP = (V)^2 \times \frac{\text{DENS}}{(1096.845)^2}$	SCFM = Standard cubic feet per minute
	V = Velocity in feet per minute
$DP = \left(\frac{M}{60 \times \text{Area}}\right)^2 \times \frac{1}{\text{DENS} \times (1096.845)^2}$	PABS = Absolute pressure in PSIA
	PATM = Atmospheric pressure in PSI
	Ps = Static pressure in inches w.c.
	T = Temperature in degrees F
	DENS = Density at actual conditions lbs/ft^3
	DENSTD = Density at standard conditions lbs/ft^3

*Courtesy of Brandt Instruments.

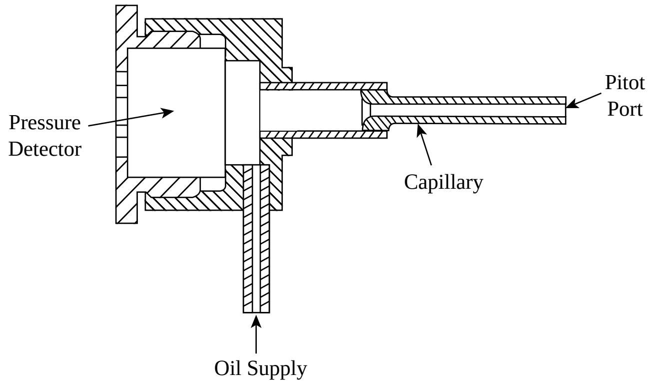


FIG. 2.16v
On highly pulsating flow measurements a minute flow of silicon oil through a capillary can serve as a pressure-averaging purge.

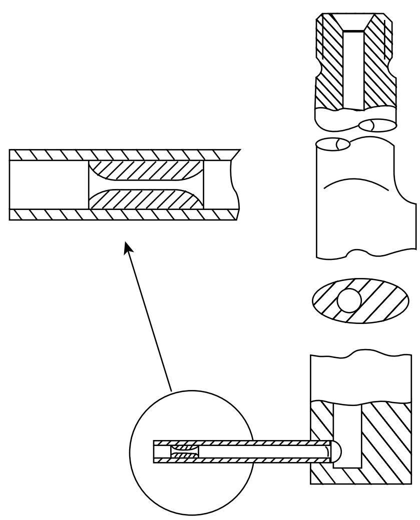


FIG. 2.16w
Pitot tube designed for pulsating flow averaging using tuned natural frequency.[6]

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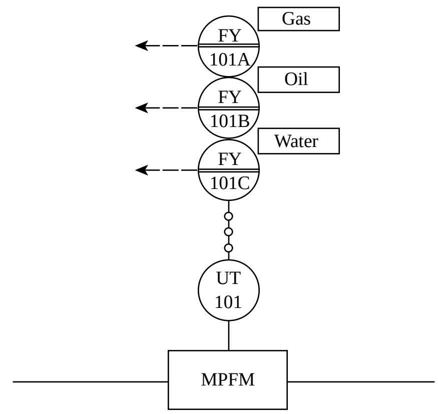
2.17 Polyphase (Oil/Water/Gas) Flowmeters

I. H. GIBSON (2003)



Flow Sheet Symbol

Design Pressure	Limited by piping design class
Operating Temperature Range	Limited by piping design class, 30 to 270°F (0 to 130°C)
Fluids	Mixtures of liquids, vapors, or gases; typically oil, water, and gas
Cost	Extremely variable, depending on line size, pressure rating, and installation requirements, starting at about $100,000 Subsea equipment commonly twice the price of surface-design units of comparable capacity
Accuracy	Five to 10%, depending on relative proportions of phases
Partial List of Suppliers	3-Phase Measurements AS (VenturiX, PhaseTester) (www.framoeng.no) Agar Corp. (www.agarcorp.com) Aker-Kvaerner (DUET) (www.kvaerner.com/kop) FlowSys AS (Topflow) FMC Technologies (www.fmctechnologies.com) Framo Engineering AS, Schlumberger (www.framoeng.no) Jiskoot Autocontrol (Mixmeter) (www.jiskoot.com) McCrometer (www.mccrometer.com) Petroleum Software Ltd. (ESMER) (www.petroleumsoftware.co.uk) Roxar AS (Fluenta, MFI) (www.roxar.com) Solartron ISA (Dualstream) (www.solartronisa.com)

Whereas most flow measurements are carefully designed to operate in single phase (gas, vapor, liquid), there are many circumstances in which the ability to distinguish the components of a liquid/vapor/gas mixture (or, indeed, multiple immiscible liquids, vapor, and gas) in the presence of solids is highly desirable.

In the production of oil/gas from unpumped petroleum wells, the flow from several thousand meters underground to the surface brings up water (commonly saline), inert gases such as carbon dioxide and nitrogen, water-saturated hydrocarbon gas (methane, ethane), hydrocarbon condensates (propane, butane, and so on), and higher hydrocarbons.

The liquids and gases do not normally travel at the same velocity, as the liquids are being dragged to the surface by the expanding gas flow. A wide variety of flow regimes are possible, depending on the mixture of phases and the geometry. A production facility may have tens of wells, and individual wells in a facility may have different mixes of ownership. This leads a requirement to be able to determine the flow of the economically interesting components from each well as accurately as possible.

The traditional method has been to use a small *test separator* that will separate the gas and the oil and water phases from a single well by gravity while production from the rest of the facility is flowing to production separators. The test separator is fitted with a full array of level and pressure controls and flowmeters (turbine, positive-displacement, orifice, and others) to enable a steady-state operation to be achieved. Commonly, the test separator is operated at a pressure slightly above the production separator to allow the streams from the test separator to be mixed with the flows out of the production separator. This requires a large amount of room and a complex valving system to enable each well to be tested separately. As pressures are commonly 1000 to 4500 PSI (7000 to 30,000 kPa) or higher, and the temperature is 150 to 270°F (65 to 130°C) at the surface, the test separator is not an inexpensive device. Individual well tests rarely can be scheduled more frequently than monthly as a result of the time taken to stabilize operation at a set of operating conditions. Even with the best of intentions, test separator measurements are notorious for inaccuracies, because quite small amounts of vapor disengaging in the liquid meters can induce errors in the 5 to 10% region.

For offshore platforms, where the cost of test separator equipment can exceed on-shore costs by many times (and especially for subsea operations, where operators cannot easily access equipment), the potential savings from an on-line method of measurement have driven the development of a variety of devices over the past 15 years. These employ a wide variety of operating principles, some of which are outlined below.

The techniques used differ depending on the ratio of liquid to gas (known as LGR or the inverse, GLR). The extreme end of the LGR (say <10% by mass) is classified as *wet gas.*

WET-GAS METERING

The standard approach for wet-gas metering treats the fluid as a gas. This uses differential-pressure devices (venturi or orifice) or vortex or ultrasonic meters. Turbine meters are unsatisfactory because even small quantities of high-velocity liquid can damage the meter. The venturi has a considerable advantage over the orifice in that it does not dam liquid behind the device, altering the flow profile. The McCrometer V-cone™ meters (Section 2.28) are also suitable for this service and have also been used for flow conditioners.

Normal ISO 5167 flow conditioners are *not* recommended for wet-gas service; not only can they dam liquids, they can induce hydrocarbon hydrate formation.

Where practical, insulation of the metering run is recommended. In some environments, trace heating may be indicated to prevent hydrate formation in the tapping connections.

Pressure tappings should be short and inclined vertically upward to avoid trapping condensate in the connections and to avoid hydrate formation.

Process gas chromatographs are not recommended for wet-gas services unless the liquid content is below 0.1%.

Venturi Meters

The venturi (Section 2.29) is much more rugged than the orifice in wet-gas service and allows for higher differential-pressure operation. With modern transmitters, turndown up to 10:1 is possible and may be necessary, given that wet-gas behavior is far more variable than that of a pure gas.

Design is generally in accordance with ISO 5761–1, although recent work by Reader-Harris et al[1] has shown that the ISO coefficients are not as well defined as claimed. The coefficients are quite sensitive to minor machining variations and, at high Reynolds number operation, the flow may break away from the throat. The coefficient can also be sensitive to the diameter-to-length ratio of the tappings; use of the “triple-T” piezometer connections advocated by ISO 5167 is impractical for wet-gas service, because the downward-facing tappings would fill with liquid.

A downstream tapping after the full pressure recovery is achieved is recommended to allow the calculation of liquid content and temperature correction to upstream conditions.

Algorithms for Wet-Gas Measurement

Differential devices used on wet-gas service will generally *overestimate* the dry-gas flow rate, and various algorithms have been developed to compensate. The Chisholm and Murdock[2] correlations were developed for orifice plates; the de Leeuw correlation has been developed for venturi meters and is an extension of the Chisholm equations.

In addition to the dry-gas flow rate, it is normally required to determine the liquid flow rate, and particularly the condensate flow rate. All three correlations (de Leeuw, Chisholm, Murdock) are based on the Lockhart–Martinelli parameter, which is a function of both liquid flow rate and density. The liquid flow rate can be determined by

- Routing the flow to a test separator
- The use of tracer techniques
- Sampling

or a combination of these. Since these are all spot-test techniques, modification to the Lockhart–Martinelli equation can be made to work in terms of the dry-gas mass fraction, which is relatively constant, provided the wetness of the gas is constant. None of these techniques is easily useful in subsea conditions, and adaptations have been made to apply dual measurements in series with devices of different geometry that allow the Lockhart–Martinelli relationship to be solved for equal values of liquid/gas. These still require considerable input of process data derived from composition.

Theory of Operation of Wet-Gas Metering

It has long been known that a gas stream carrying a well-dispersed liquid content through a differential flow element (orifice, nozzle, venturi, or V-cone) will develop a higher differential than that due to the corresponding gas flow. If the properties of the gas and liquid are known, it is possible to calculate the relative content of liquid in the gas.

The following development has been adapted from the UK DTI Oil and Gas Division’s Guidance Notes for

Petroleum Measurement under the Petroleum (Production) Regulations.[2]

de Leeuw Wet-Gas Venturi Correlation

de Leeuw[3] has shown that the real gas mass flow rate can be derived from the following equations (all equations are based on SI units):

$$Q_{\text{real gas}} = \frac{Q_{\text{uncorrected gas}}}{\sqrt{(1+CX+X^2)}} \qquad \textbf{2.17(1)}$$

where $Q_{\text{uncorrected gas}}$ = uncorrected gas mass flow rate as indicated by the venturi meter using the following equation:

$$Q_{\text{uncorrected gas}} = C_{\text{gas}} \varepsilon \pi d^2 \frac{\sqrt{(2\rho_{\text{gas}} \Delta P)}}{4\sqrt{1-\beta^4}} \qquad \textbf{2.17(2)}$$

where
C_{gas} = discharge coefficient of the venturi flowmeter in dry gas as determined through calibration
ε = expansibility of gas in venturi as defined by ISO 5167-1
d = throat diameter of the venturi flowmeter (corrected for temperature)
ρ_{gas} = gas density at upstream conditions
ΔP = raw differential pressure as measured by the transmitter
β = ratio of d to D, the pipe diameter

and X is the *Lockhart–Martinelli* parameter, which is derived as follows:

$$X = \frac{Q_{\text{liquid}}}{Q_{\text{real gas}}} * \sqrt{\frac{\rho_{\text{liquid}}}{\rho_{\text{gas}}}} \qquad \textbf{2.17(3)}$$

where
Q_{liquid} = combined liquid flow rate through the venturi flowmeter
ρ_{liquid} = combined liquid density

The coefficient C is given by the following equation:

$$C = \left(\frac{\rho_{\text{liquid}}}{\rho_{\text{gas}}}\right)^n + \left(\frac{\rho_{\text{gas}}}{\rho_{\text{liquid}}}\right)^n \qquad \textbf{2.17(4)}$$

where the exponent n is given by

$$n = 0.606(1-e^{-0.746 Fr_g}) \quad \text{for } Fr_g \geq 1.5 \qquad \textbf{2.17(5)}$$

$$n = 0.41 \quad \text{for } 0.5 \leq Fr_g \leq 1.5 \qquad \textbf{2.17(6)}$$

and Fr_g is the gas Froude number given by

$$Fr_g = \left[\frac{V_{\text{gas}}}{\sqrt{(gD)}}\right] * \left[\frac{\sqrt{\rho_{\text{gas}}}}{\sqrt{(\rho_{\text{liquid}} - \rho_{\text{gas}})}}\right] \qquad \textbf{2.17(7)}$$

where
V_{gas} = superficial gas pipe velocity
g = local acceleration due to gravity

V_{gas} can be derived using an iterative method and "seeding" a velocity based on the uncorrected mass flow rate. The first pass equation is

$$V_{\text{gas}} = \frac{4 * Q_{\text{uncorrected gas}}}{\rho_{\text{gas}} \pi D^2} \qquad \textbf{2.17(8)}$$

For further iterations $Q_{\text{uncorrected gas}}$ is replaced by consecutive $Q_{\text{real gas}}$ values until the equation converges to a solution.

Liquid Mass Flow Rate Correction Algorithm

The resultant liquid mass flow rates can be derived from the following equations:

$$Q_{\text{total}} = Q_{\text{real gas}} + Q_{\text{liquid}} \qquad \textbf{2.17(9)}$$

Condensate mass flow rate

$$Q_{\text{condensate}} = Q_{\text{total}} * \zeta_{\text{condensate}} \qquad \textbf{2.17(10)}$$

Water mass flow rate

$$Q_{\text{water}} = Q_{\text{total}} * \zeta_{\text{water}} \qquad \textbf{2.17(11)}$$

Methanol (or glycol) mass flow rate

$$Q_{\text{methanol}} = Q_{\text{total}} * \zeta_{\text{methanol}} \qquad \textbf{2.17(12)}$$

where
$\zeta_{\text{condensate}}$ = condensate mass fraction
ζ_{water} = water mass fraction
ζ_{methanol} = methanol mass fraction

In turn,

$$\zeta_{\text{condensate}} = X * \psi_{\text{condensate}} \qquad \textbf{2.17(13)}$$

$$\zeta_{\text{water}} = X * \psi_{\text{water}} \qquad \textbf{2.17(14)}$$

$$\zeta_{\text{methanol}} = X * \psi_{\text{methanol}} \qquad \textbf{2.17(15)}$$

where

$\psi_{condensate}$ = condensate-to-gas mass fraction
ψ_{water} = water-to-gas mass fraction
$\psi_{methanol}$ = methanol-to-gas mass fraction (methanol injection is commonly used to suppress hydrocarbon hydrate formation)

Liquid Density Calculation Algorithm

The liquid density can be calculated as follows:

$$\rho_{liquid} = \frac{\psi_{liquid}}{\left(\left(\frac{\psi_{condensate}}{\rho_{condensate}}\right) + \left(\frac{\psi_{water}}{\rho_{water}}\right) + \left(\frac{\psi_{methanol}}{\rho_{methanol}}\right)\right)} \quad \textbf{2.17(16)}$$

where

ψ_{liquid} = total liquid to gas mass ratio
ρ_{liquid} = density of liquid
$\rho_{condensate}$ = density of hydrocarbon condensate
ρ_{water} = density of water
$\rho_{methanol}$ = density of methanol
$\rho_{condensate}$ = is derived from the condensate base density and corrected for temperature and pressure (Ctl and Cpl)

Corrections from the standard API MPMS11.2.1M may be applied. However, for improved accuracy, it is recommended that samples of the condensate be obtained and analyzed to derive specific correction factors. The values of K_0 and K_1 for crude oil (613.9723 and 0, respectively) are not ideal for condensate, and the alternatives from the standards referred to above may be no better.

Water and methanol densities can be derived as follows:

$$t = (t_m + 273.15) * \left(\frac{P_3}{P_1}\right) K_3 - 273.15 \quad \textbf{2.17(17)}$$

where

t = temperature at the inlet of the venturi
A, B, C = water constants (e.g., –0.0001732, –0.1307, 1040)
D, E, F = methanol constants (e.g., 0.0000713, –0.3344, 540)

The correct values of these methanol and water constants may vary due to salinity or product type. It is therefore advisable to have the liquids analyzed to determine appropriate values.

Upstream Temperature Correction and Pressure Recovery

The correction for downstream measured temperature to upstream temperature (in degrees centigrade) at the inlet is given by

$$t = (t_m + 273.15) * \left(\frac{P_3}{P_1}\right) K_3 - 273.15 \quad \textbf{2.17(18)}$$

where

t_m = measured temperature
P_3 = fully recovered downstream pressure
P_1 = pressure measured at the upstream tapping
K_3 = downstream to upstream temperature correction exponent

P_3 can be measured using a third pressure tapping or calculated (in bar) from the following empirical equation from Miller:[4]

$$P_3 = P_1 - 10^{-3} * \Delta\omega \quad \textbf{2.17(19)}$$

where

$$\Delta\omega = (A\beta^2 + B\beta + C) * \Delta P \quad \textbf{2.17(20)}$$

and the constants A, B, and C, for venturies with 7 and 15° exit cone angles, are as follows:

7° cone angle	$A = 0.38$	$B = 0.42$	$C = 0.218$
15° cone angle	$A = 0.59$	$B = 0.86$	$C = 0.436$

Gas Mass Fraction Estimation Using Tracer Techniques

The gas mass fraction can be estimated as follows:

1. Perform the tracer flow technique to determine condensate and water flow rates and mass ratios. This uses concentrated oil-soluble and water-soluble fluorescent chemicals, injected upstream and partially recovered by sampling downstream of the flowmeter.
2. Analyze the condensate to determine base density.
3. Sample the gas to determine gas density.
4. Record the total uncorrected gas flow from venturi during the tracer flow technique.
5. Determine the dry “first pass” gas mass fraction and liquid-to-gas ratio based on the recorded uncorrected gas flow and tracer flow results (corrections for methanol injection after completion of tracer technique may be required).
6. *Seed* values from the last stage into the wet-gas venturi flow calculation to determine a “first pass” corrected gas flow rate.
7. *Re-seed* this value into the calculation, correcting gas mass ratio and liquid-to-gas ratio.
8. Iterate the process until the corrected gas flow rate converges.

Solartron-ISA Dualstream II™ Theory

The Solartron-ISA Dualstream™ II, originally developed by British Gas, extends the theory noted above by fitting two dissimilar pressure differential devices in series. These have differing Lockhart–Martinelli characteristics, and the

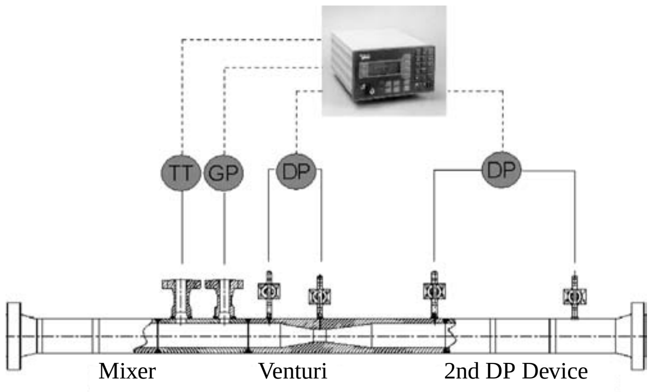


FIG. 2.17a
Solartron—ISA Dualstream II™ wet gas flowmeter.

combination can determine changes in the gas-to-liquid ratio. The venturi will generate an indicated flow rate. This can be corrected to generate a "true" gas flow rate using the equations in previous sections.

The second "DP device" will generate a second indicated flow rate. This flow rate can be corrected to give a "true" gas flow rate using similar relations.

A simultaneous equation can be formed from these flow rates:

$$Q_g = \frac{Q_{gi\,(\text{venturi})}}{1 + M_{(\text{venturi})} \dfrac{(1-x)}{x} \dfrac{C_g}{C_l} \varepsilon_g \sqrt{\dfrac{\rho_g}{\rho_l}}} = \frac{Q_{gi\,(\text{2nd Dp})}}{1 + M_{(\text{2nd Dp})} \dfrac{(1-x)}{x} \dfrac{C_g}{C_l} \varepsilon_g \sqrt{\dfrac{\rho_g}{\rho_l}}} \qquad \textbf{2.17(21)}$$

$$x = \frac{\sqrt{\dfrac{\rho_g}{\rho_l}} \left(\dfrac{Q_{gi\,(\text{2nd Dp})}}{Q_{gi\,(\text{venturi})}} M_{(\text{venturi})} - M_{(\text{2nd Dp})} \right)}{\left(1 - M_{(\text{2nd Dp})} \sqrt{\dfrac{\rho_g}{\rho_l}}\right) - \dfrac{Q_{gi\,(\text{2nd Dp})}}{Q_{gi\,(\text{venturi})}} \left(1 - M_{(\text{venturi})} \sqrt{\dfrac{\rho_g}{\rho_l}}\right)} \qquad \textbf{2.17(22)}$$

This enables a continuous estimation of the liquid-to-gas ratio without the necessity for tracer measurements, and it is particularly useful sub-sea, where tracer measurements are impractical with current technology.

MULTIPHASE FLOWMETERS

The various true multiphase flowmeters can be effective from straight liquid through to 95 or 97% gas. Some meters, such as the Agar MPFM400 and Jiskoot, attain the extreme gas end by using an in-line separator to send the wet gas through a wet-gas meter and the remaining gas, with oil and water, through a separate multiphase flowmeter section. No standards exist as yet to assist engineers in designing multiphase metering systems, and there are wide variations in the methods used to define *accuracy* and performance. When considering a manufacturer's performance and accuracy statements, it is essential to understand the implications of accuracies quoted in different ways. There are three common ways in which multiphase meter accuracies are presented:

1. Percent phase volume flow rate
2. Percent total multiphase flow rate
3. Percent gas and liquid flow rate plus absolute uncertainty of water cut in liquid phase

Method 1 is favored by metrologists and clearly represents performance as stated. This method may not be the most practical for extreme cases of phase fractionation.

Methods 2 and 3, whereas quoting relatively small numbers on the order of 5 to 10% for gas/liquid phase uncertainties and 2 or 3% for percentage water cut, may nevertheless exhibit very large individual phase errors of 100% or more, depending on the absolute value of the percentage water.

The first requirement for a mixed liquid phase is to distinguish hydrocarbon from water. If the liquid phase is oil-continuous, typically water less than 40% liquid hydrocarbon, then dielectric constant measurement at microwave frequencies can determine the water fraction. The dielectric constant of dry hydrocarbon is in the order of 2 to 4, depending on composition, while water is 82, giving a sensitive means of measurement.

For higher water content, the measuring element will short out in a water-continuous phase, but density measurement can distinguish water from oil. This requires stream-specific characterization, as the composition and density of the liquid is pressure and temperature dependent.

The next requirement is to distinguish the flow of liquid from the flow of gas in a system where the two will try to separate and travel at different velocities. Flow conditioning in these systems is commonly provided by a horizontal branch-in, vertical-out tee, which acts as a mixer. Cross-correlation flowmeters (see Section 2.5) used by some suppliers apply nuclear techniques to measure the density of the stream twice, a short vertical distance apart, and correlate the fluctuations in density with time; others use electrical characteristics in a similar manner.

As it is difficult to distinguish the differing velocities of liquid and gas, it is common to measure the velocity of one phase and use flow-modeling techniques to estimate the velocity of the other phase.

Most of the techniques are limited by the liquid/gas ratio (LGR). Lean gas streams, with less than 5% liquid, are difficult to measure given that the density of the gas stream can be comparable with that of the liquid phase; at 3000 PSI (21,000 kPa), the gas phase can be on the order of 200 kg/m^3 with the liquid phase perhaps 600 kg/m.^{3} So, a change from 5% liquid to 4% liquid is a 20% variation in liquid, but it will

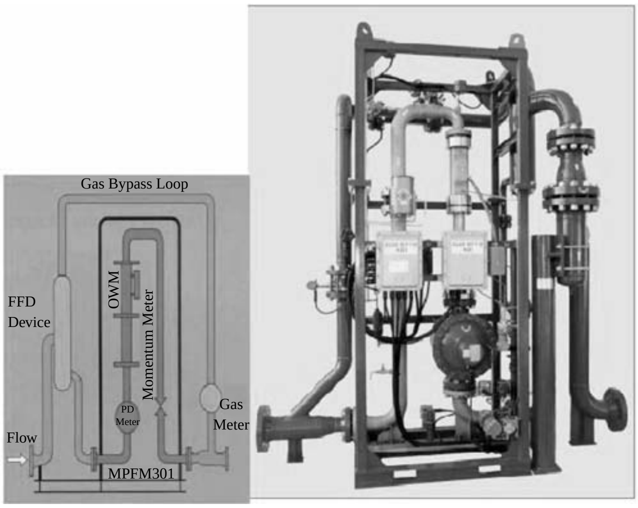


FIG. 2.17b
Agar MPFM 400 high void fraction meter.

only change the density by less than 2%. To avoid this, one supplier (AGAR) uses a centrifugal separator to separate much of the gas from a remaining three-phase mixture, measure this separately, and then mixes it back after the other stream has been measured. Removing 80% of the gas enables the multiphase meter section to be much smaller and more sensitive to the valuable liquid hydrocarbon. The true volumetric flow of the multiphase mixture is measured by a positive-displacement Oval™ gear meter, and venturi techniques and microwave water content distinguish the different phases.

The orientation of a multiphase flowmeter can strongly influence the multiphase flow regime. In systems with medium to high gas content and low velocity, vertical upflow can find the gas phase unable to continuously sweep the liquid phase forward, and the liquid may recycle backward, leading to metering errors and to slug flow. This offers a significant low-end constraint on flow through devices of fixed geometry, which will differ between devices of similar size.

Horizontal-flow installations can show internal segregation, with gas, oil, and water layers traveling at different velocities. Again, maintaining a high velocity helps to mix the phases, but the upstream piping layout may contribute to slugging, which the meter system can do little to correct.

Measurement in multiphase flow is notable by widely varying conditions under nominally constant flow. In slug flow, the liquid fraction can vary between almost zero in the region after a liquid slug to almost 100% inside the slug. Significant fluctuations will also be present in annular and churn flow patterns.

The pressure drop of a liquid slug passing through a venturi meter can be five times higher than the average pressure drop for the flow; the minimum pressure drop in the same flow, corresponding to the *film* region, can be 20% of the average. Therefore, a venturi meter would experience pressure drop varying by 25:1 at a nominally steady multiphase production condition. This is one reason for the

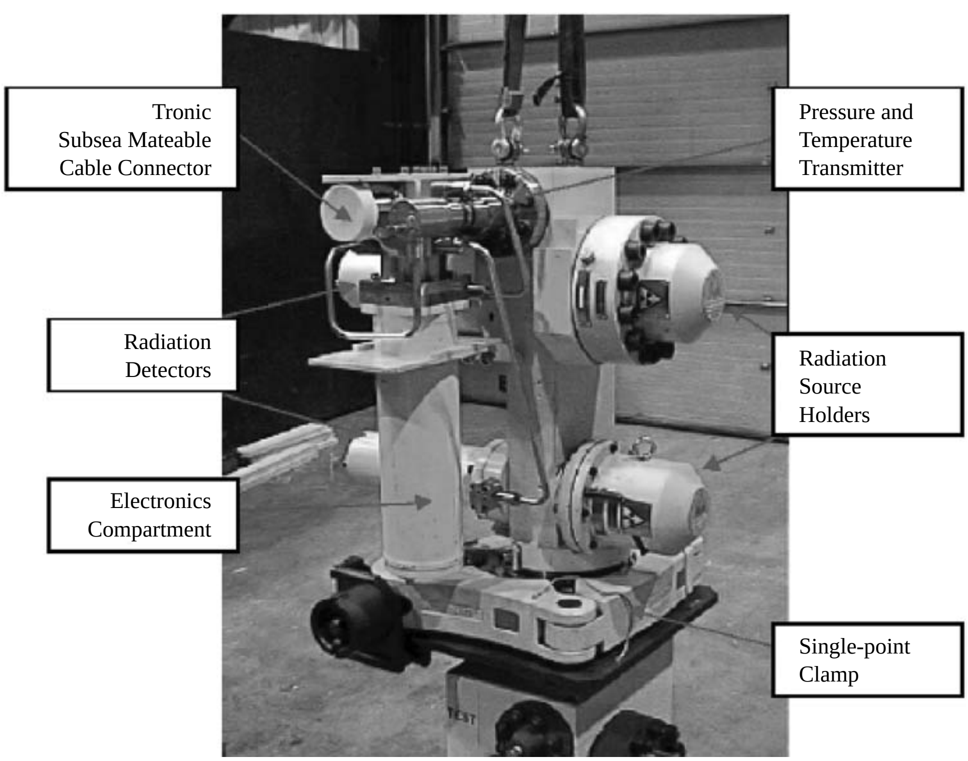


FIG. 2.17c
Aker-Kvaerner "DUET" subsea multiphase flowmeter.

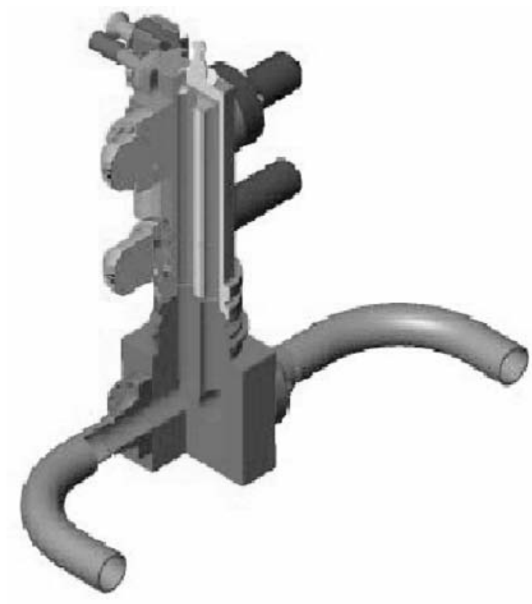


FIG. 2.17d
Aker-Kvaerner "DUET" subsea multiphase flowmeter sectional drawing.

attraction of correlation flowmetering techniques, which do not experience such extremes yet require (and see) appreciable fluctuations in physical properties in the short term.

To reduce the uncertainty associated with measurement of a parameter that fluctuates over such a wide range, many samples are required over a relatively long measuring period.

When a multiphase meter is located at the receiving end of a pipeline, the resulting measurement is influenced by the flow into the line (which may be combined from several wells); the flow patterns developing along the line; the elevation changes along the line, which can trap liquid at low points; the outlet pressure changes; and other fluctuations. As can be imagined, the flow out of such a pipeline varies considerably, and the measuring equipment must be specified to cover the full range of the variation, usually based on inadequate data.

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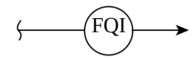
2.18 Positive-Displacement Gas Flowmeters



Flow Sheet Symbol

R. SIEV (1969) **G. M. CRABTREE** (1982, 1995) **JESSE YODER** (2003)

Type of Design	A. Positive-displacement B. High-precision
Design Pressures	Low-pressure designs available from 5 to 100 PSIG (0.34 to 6.9 bars); high-pressure units available up to 1440 PSIG (100 bars)
Design Temperatures	Standard units can be used from –30 to 140°F (–34 to 60°C)
Materials of Construction	Aluminum, steel, plastics, and synthetic elastomers
Inaccuracy	A. 0.5 to 1% of registration B. 0.5% of actual flow over 50:1 range
Costs	A household gas meter for 250 SCFH (7 SCMH) capacity costs about $150. A 50,000 SCFH (1416 SCMH) capacity, diaphragm-type, displacement-type flowmeter in cast aluminum for natural gas service costs about $5000. For natural gas service a 70,000 SCFH (1983 SCMH) rotary positive-displacement meter in cast aluminum costs about $3000.
Partial List of Suppliers	American Meter Co. (A) Actaris Metering System (A) Bopp & Reuther (www.burhm.de) (A) Dresser Instrument (Root Meter) (www.dresserinstruments.com) (A) Elster-AMCO (Germany) (A) Invensys Process Systems (www.invensysips.com) (A) Instromet (A) Kimmon Mfg. (Japan) (A) Liqua-Tech Controls Pierburg Instruments Inc. (www.pierburginstruments.com) (B) Ritter (Germany) RMG (Germany) Romet Ltd. (Canada) (A) Schlumberger Measurement Div. (www.slb.com/rms/measurement) (A)

Positive-displacement gas meters measure by internally passing isolated volumes of gas that successively fill and empty compartments with a fixed quantity of gas. The filling-and-emptying process is controlled by suitable valving and is translated into rotary motion to operate a calibrated register or index that indicates the total volume of gas passed through the meter.

The liquid sealed drum meter is the oldest commercial positive-displacement gas meter (see Figure 2.18a). Developed in the early 1800s, it was used for many years during the gaslight era. This type of meter is still available today and remains one of the most accurate of the displacement-type meters. Applications of the liquid sealed drum meter today

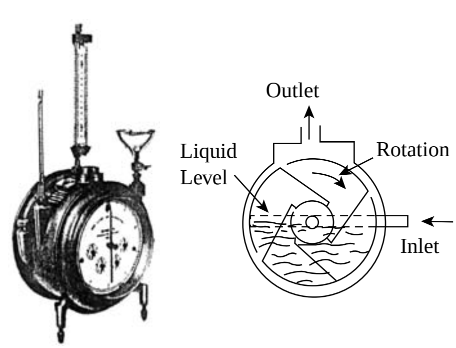
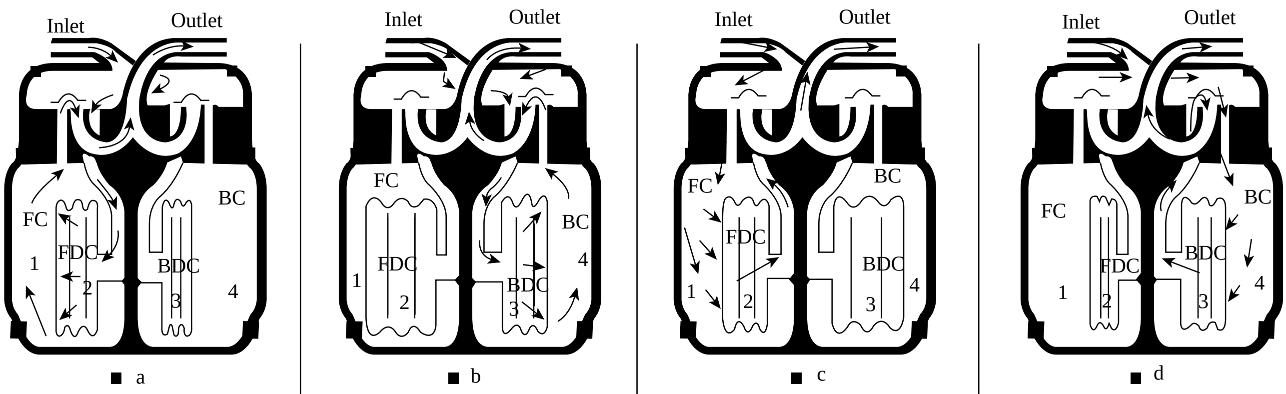


FIG. 2.18a
The liquid sealed drum meter.



■ a	■ b	■ c	■ d
Chamber 1 is emptying, 2 is filling, 3 is empty, and 4 has just filled.	Chamber 1 is now empty, 2 is full, 3 is filling, and 4 is emptying.	Chamber 1 is filling, 2 is emptying, 3 has filled, and 4 has emptied.	Chamber 1 is now completely filled, 2 is empty, 3 is emptying, and 4 is filling.

FIG. 2.18b
The four-chamber diaphragm meter; FC = front chamber; BC = back chamber; FDC = front diaphragm; BDC = back diaphragm chamber.

include laboratory work, appliance testing, pilot plant measurements, and as a calibration standard for other meter types.

Some of the inherent difficulties with the liquid sealed meter, such as changes in liquid level and freezing, were overcome in the 1840s with the development of the diaphragm-type positive-displacement meter. Thomas Glover is credited with inventing the first two-diaphragm, sliding-vane meters in 1843, in England. The early meters were constructed with sheepskin diaphragms and sheet metal enclosures. Today, meters are made of cast aluminum with synthetic rubber-on-cloth diaphragms. The principle of operation, however, has remained the same for almost 150 years. However, many material, product design, manufacturing, and calibration changes have occurred during that time.

THE DIAPHRAGM METER

The operating principle of the four-chamber diaphragm meter is illustrated in Figure 2.18b. The measurement section consists of four chambers formed by the volumes between the diaphragms and the center partition and between the diaphragms and the meter casing. Differential pressure across the diaphragms extends one diaphragm and contracts the other, alternately filling and emptying the four compartments. The control for the process is through the “D” slide valves that are synchronized with the diaphragm motion and timed to produce a smooth flow of gas by means of a crank mechanism. The crank and valve mechanism is designed and adjusted with no *top-dead-center* to prevent the meter from stalling. The rotating crank mechanism is connected through suitable gearing to the index, which registers the total volume passed by the meter.

The rating of small diaphragm meters is usually specified in cubic feet per hour (0.03 m^3/h) of 0.6 specific gravity gas that results in a pressure drop of 0.5-in. water column (0.13 kPa). Larger meters are often rated for flow at 2 in. water column (0.5 kPa) differential.

Since most meters are sold to gas utility companies that sell natural gas with a specific gravity of approximately 0.6, it may be necessary to determine the flow rating of a diaphragm for other gases. This is accomplished by the following equation:

$$Q_n = Q_c\sqrt{\frac{(SG)_c}{(SG)_n}} \qquad \textbf{2.18(1)}$$

where
Q_n = new flow rating (ft^3/h)*
Q_c = meter rating (ft^3/h)
$(SG)_c$ = specific gravity for which meter is rated (usually 0.6)
$(SG)_n$ = specific gravity of new gas

The inaccuracy of diaphragm positive-displacement meters is typically ±1% of registration over a range in excess of 200:1. This accuracy is maintained over many years of service. Deterioration of meter accuracy is rare unless unusual conditions of dirt, wear, or moisture in the gas are present.

ROTARY METERS

Rotary meters have one or more rotating parts that implement their measurement operation. Meter design enables them to operate at higher rates of speed than diaphragm meters. For this reason, they can meter higher gas volumes than diaphragm meters. In many cases, rotary meters have built-in temperature compensation to avoid measurement errors based on temperature variations.

* For SI units, refer to Appendix.

There are three types of rotary positive-displacement meters in use today for gas flow measurement:

- Lobed impeller
- Sliding vane
- Rotating vane

The Lobed Impeller

The lobed-impeller meter (described in Section 2.19, "Positive-Displacement Liquid Meters and Provers") is used for high-volume measurement up to 100,000 ft^3/h (up to 3000 m^3/h). This meter has a housing upon which two figure-eight impellers are mounted. The rotation is caused by a pressure differential that is set up across the meter. In this meter, the close clearance of moving parts requires the use of upstream filters to prevent deterioration of accuracy performance. Typically, the inaccuracy of lobed-impeller meters is ±1% over a 10:1 flow range at pressure drops of approximately 0.1 PSI (0.7 kPa).

Sliding-Vane Meters

A sliding-vane meter has four radial vanes in a single rotating drum that is eccentrically mounted. The rotation of the drum is caused by differential pressure against the vanes. When the drum revolves a single time, four volumes of gas are passed. The meter counts the number of revolutions to provide a readout of total volume.

Rotating-Vane Meters

The rotating-vane meter, as illustrated in Figure 2.18c, is an improvement on the lobed-impeller meter. Here, four compartments formed by the vanes rotate in the same direction as a rotating gate. The fixed volumes of gas are swept through the meter by the vanes, which are passed from inlet side to outlet side through the gate. Gears synchronize the motion of the vanes and gate. Typical inaccuracy for the rotating vane meter is ±1% over a 25:1 range at pressure drops of 0.05 in. of water column (0.013 kPa).

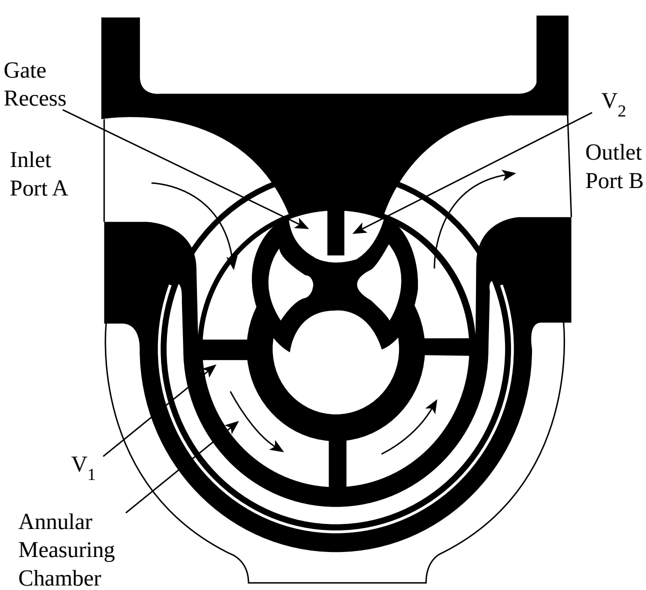


FIG. 2.18c
The rotating-vane meter.

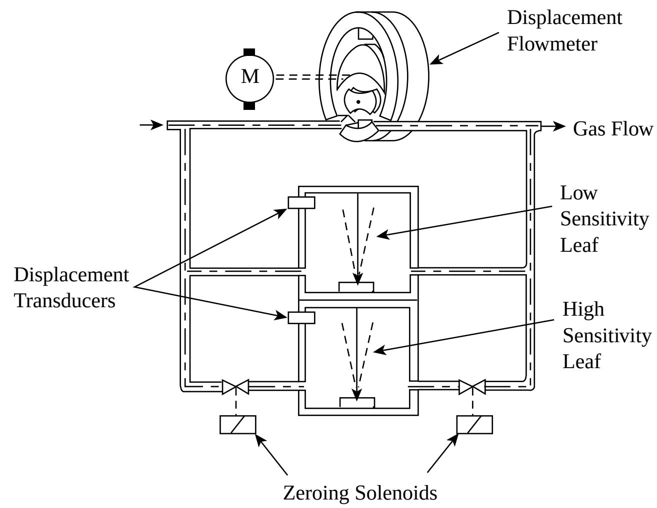


FIG. 2.18d
High-precision displacement flowmeter for gas service. (Courtesy of Pierburg Instruments.)

HIGH-PRECISION GAS FLOWMETER

For the high-precision measurement of airflows in engine test rigs, positive-displacement flowmeters are used. High precision and high rangeability are achieved by eliminating the pressure drop and thereby eliminating the slip or leakage flows. This is achieved by providing a motor drive for the displacement element and using it to introduce only as much driving energy as is needed to keep the pressures at the inlet and outlet of the meter equal (Figure 2.18d). This flowmeter uses high-sensitivity leaves to detect the pressure differential and displacement transducers to detect the deflection of the leaves. The flowmeter is also provided with automatic rezeroing capability through periodic solenoid isolation of the high-sensitivity leaves.

This flowmeter is claimed to provide a reading with only a 0.25% error over a 50:1 range and a 0.5% error over a 100:1 range. The meter is designed for ambient operating temperatures and 30 PSIG (2 bars) operating pressures. The different models of this flowmeter can detect air or gas flows from 0.3 to 1500 ACFM (0.6 to 2500 ACMH).

APPLICATION NOTES

All displacement gas meters can be used to measure any clean, dry gas that is compatible with the meters' construction materials and flow and pressure ratings. Dirt and moisture are the worst enemies of good meter performance; inlet filtering should be used when indicated. Since all gases change

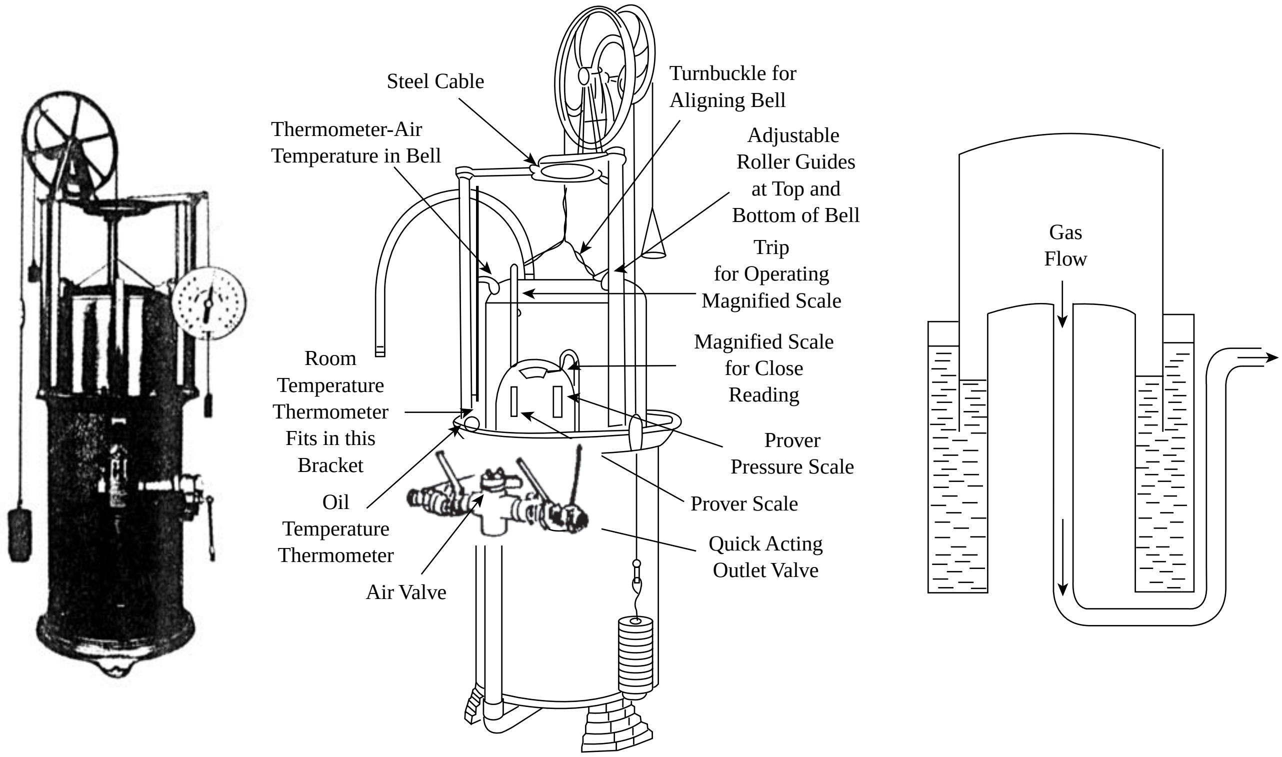


FIG. 2.18e
The construction of a meter prover.

volume with pressure and temperature changes, these sources of possible error should be controlled or compensated. The national standard cubic foot of fuel gas is at 14.73 PSIA and 60°F; significant deviation from these values should be accounted for in measuring standard gas volumes. At elevated pressures and lower temperatures, a deviation from the ideal gas laws occurs, requiring the application of a compressibility factor to the measured volumes.

TESTING AND CALIBRATION

The testing (or *proving,* as it is called in the gas utility industry) of gas meters is usually done using a special type of gasometer referred to as a *prover.* The construction of a meter prover is shown in Figure 2.18e. An accurately calibrated "bell" of cylindrical shape is sealed over a tank by a suitable liquid. The lowering of the bell discharges a known volume of air through the meter under test to compare the volumes indicated. Meter provers are typically supplied to discharge volumes of 2, 5, and 10 ft^3 (0.06, 0.15, and 0.3 m^3), and larger provers of several hundred cubic foot capacity are in use by meter manufacturers and gas utility companies. The volumetric inaccuracy of meter provers is on the order of ±0.1% as determined by physical measurement and comparison with more accurate volumetric standards.

Other standards used to calibrate gas meters are calibrated orifices and critical flow nozzles. These devices compare rates of flow rather than fixed volumes and typically have inaccuracy ratings from ±0.15 to ± 0.5%.

ADVANTAGES

The chief advantages of positive-displacement flowmeters for gas applications are their high accuracy and wide rangeability. The chief disadvantages of these meters are maintenance costs and the fact that wear can degrade their performance.

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2.19 Positive-Displacement Liquid Meters and Provers

Flow Sheet Symbol

R. SIEV (1969) **J. B. STODDARD** (1995) **B. G. LIPTÁK** (1982, 2003)

Types of Designs	A. Impeller, propeller, turbine B. Nutating disc C. Oval gear, C-1 if toothless D. Piston E. Rotating vane F. Viscous helix G. High-precision, specialized, low-flow, and so on H. Prover
Design Pressure	To 3000 PSIG (21 MPa)
Design Temperature	From –450°F (–268°C) to 560°F (293°C)
Strainer Required	Yes
Materials of Construction	Bronze, cast iron, aluminum, steel, stainless steel, Monel®, Hastelloy®, and plastics
Size Range	0.25 to 16 in. (6 to 406 mm)
Flow Range	From 0.01 GPH to 20,000 GPM (0.04 l/h to 75 m^3/m)
Rangeability	From 3:1 to >100:1 (for specialized designs), 10:1 about average
Inaccuracy	Ranges from ±0.1 to ±2% of actual flow; typical average error ±1/2% of actual flow, dropping as size increases
Cost	A 1 in. (25 mm) bronze disk-type water meter with 2 to 3% error costs about $750. Plastic-piston meters for laboratory applications in 1- and 2-in. (25- and 50-mm) sizes are $600 and $1200. A 1-in. (25-mm) toothless oval meter for high-viscosity service in type 316 SS is $2500. A 1-in. (25-mm) oval flowmeter for LPG service with ductile iron housing complete and valve, vapor eliminator, and register with printer, about $3000. A 2-in. (50-mm) piston meter, in steel construction, having 0.5% error and provided with register, preset valve, and ticket printer costs about $5000 to $6000. A 6-in. (150-mm) flanged, bi-rotor meter for fuel oil service with ductile iron preset valve, impulse contactor, large dial register, and ticket printer costs about $12,000 to $15,000. Prover costs range from $50,000 to $300,000 depending on size, materials of construction, and control accessories.
*Partial List of Suppliers**	Badger Meter Inc. (www.badgermeter.com) (B, D) Barton Instrument Systems LLC (www.barton-instruments.com) (A, E) Brooks Instrument (www.emersonprocess.com) (A, C, D, F, H)

* The most popular are Brooks Instrument, Smith Meter Inc., and Badger Meter Inc.

Cole-Parmer Instrument Co. (www.coleparmer.com) (D)
Daniel Measurement and Control (www.danielind.com) (E, H)
Dresser Instrument (www.ashcroft.com) (A)
Flow Technology Inc. (www.ftimeters.com) (H)
Kobold Instruments Inc. (www.koboldusa.com) (F, G)
Liquid Controls Inc. (www.lcmeter.com) (A, E)
Max Machinery Inc. (www.maxmachinery.com) (C, D, F)
Omega Engineering Inc. (www.omega.com) (C1)
PLU of Pierburg GmbH (www.pierburg-instruments.de) (G)
Schlumberger Measurement Div. (www.slb.com/rms/measurement) (A, B, D)
Smith Systems Inc., (www.smith-systems-inc.com) (A, C, D, E)

Positive-displacement meters split the flow of liquids into separate known volumes, the size of which are based on the physical dimensions of the meter. The meters act as counters or totalizers of the number of these volumes as they pass through. These mechanical meters have one or more moving parts in contact with the flow stream and physically separate the fluid into increments. Energy to drive the moving parts is extracted from the flowing stream itself, resulting in a pressure loss through the meter. The error of these meters depends on the clearances between the moving and stationary parts. The smaller the clearance and the longer the length of the leakage path, the better the precision of the meter. For this reason, meter accuracy tends to increase with larger meter sizes.

OVERVIEW

Positive-displacement meters for liquids are among the most widely used volumetric flow sensors for batch-size measurement applications and when fluid is bought and sold on a contract basis. A wide variety of meters, covering a broad spectrum of requirements, are available. Their good accuracy, wide rangeability, and ready availability warrant their consideration when selecting a volumetric meter.

These flowmeters are especially useful when the fluid to be measured is free of any entrained solids. A typical example is the measurement of water delivered to homes, factories, office buildings, and so forth. On the other hand, some designs are well suited for viscous liquid applications.

Wear on parts, with the resulting change in clearance dimensions, introduces the major source of error over the service life of the meter. Leakage error increases with dropping process fluid viscosity but remains relatively constant with time. In larger meters, temperature variations and the resulting change in fluid density and viscosity must also be taken into consideration.

Positive-displacement meters provide good accuracy (±0.25% of flow) and high rangeability (15:1). They are repeatable to ±0.05% of flow. Some designs are suited for high- or variable-viscosity services (up to or even exceeding 100 cSt). They require no power supplies for their operation (only for remote transmission) and are available with a wide variety of readout devices. Their performance is virtually unaffected by upstream piping configuration. Positive-displacement meters are excellent for batch processes, mixing, and blending applications.

These meters are simple and easy to maintain by regular maintenance personnel using standard tools. No specially trained crews or special calibration instruments are needed. On the other hand, because of the close tolerances of the moving parts, they are subject to wear and maintenance, and recalibration is required at frequent intervals. On corrosive services, this may result in high costs.

Positive-displacement meters require relatively expensive precision-machined parts to achieve the small clearances that guarantee their high accuracy. From this it follows that the liquids metered must be clean, because wear can rapidly destroy precision. Contaminant particle size must be kept below 100 microns, and most of these meters are not adaptable to the metering of slurries. Positive-displacement flowmeters are expensive in larger sizes or in special materials. They can be damaged by overspeeding and can require high pressure drops. In general, they are not suited for dirty, nonlubricating, or abrasive services.

ROTATING LOBE AND IMPELLER (TYPE A)

In this type of meter, two lobed impellers rotate in opposite directions within the housing (Figure 2.19a). They are geared together to maintain a fixed relative position, so a fixed volume of liquid is displaced by each revolution. A register is geared to one of the impellers. These meters are normally built for 2- to 24-in. (50- to 610-mm) pipe sizes, and their capacities (upper limits of their ranges) range from 8 to 17,500 GPM (30.4 to 66,500 l/min).

The advantages of this design include good repeatability (0.015%) at high flows, the availability of a range of materials of construction, and high operating pressures (1200 PSIG or 8300 kPa) and temperatures (400°F or 205°C).

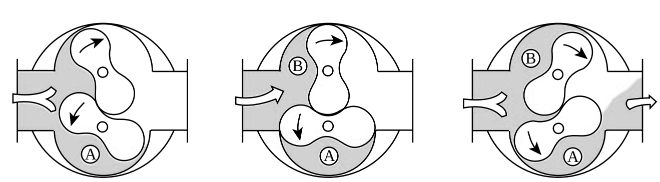

FIG. 2.19a
Rotating lobe meter.

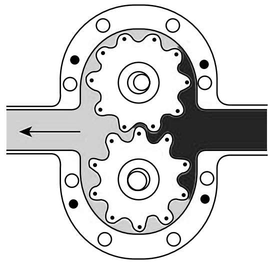

FIG. 2.19b
Rotating impeller flowmeter. (Courtesy of Flowdata Inc.)

The disadvantages include loss of accuracy at low flows because of the large size, heavy weight, and high cost.

The rotating impeller design is illustrated in Figure 2.19b. It has only two moving parts: the two impellers, which are made out of wear-, abrasion-, and corrosion-resistant thermoplastics. Operation is based on a proximity switch sensing the passage of magnets that are implanted in the impeller lobes and transmitting the resultant pulses to a counter. Units are available from 0.125- to 4-in. (3- to 100-mm) sizes with up to 3000 PSIG (21 MPa) pressure and 0 to 400°F (205°C) temperature ratings. The design is suited for high-viscosity operation, and the claimed precision and rangeabilities are also high.

NUTATING DISK (TYPE B)

The nutating disk meter is used extensively for residential water service. The moving assembly, which separates the fluid into volume increments, consists of an assembly of a radially slotted disk with an integral ball bearing and an axial pin (see Figure 2.19c). This part fits into and divides the metering chamber into four volumes—two above the disk on the inlet side and two below the disk on the outlet side. As the liquid flows through the meter, the pressure drop from inlet to outlet causes the disk to wobble, or *nutate*. For each cycle, the meter displaces a volume of liquid equal to the volume of the metering chamber minus the volume of the disk assembly. The end of an axial pin, which moves in a circular motion, drives a cam that is connected to a gear train and to a totalizing register. This flowmeter measures the liquids with an error range of about ±1 to 2% of actual flow. It is built only for smaller pipe sizes. Its temperature range is from −300 to 250°F (–150 to 120°C), and its maximum working pressure rating is 150 PSIG (1034 kPa). On cold water service, the capacity ranges are approximately as follows:

Size	*Capacity*
0.5 in. (13 mm)	2 to 20 GPM (7.5 to 75 l/min)
1 in. (25 mm)	5 to 50 GPM (19 to 190 l/min)
1.5 in. (38 mm)	10 to 100 GPM (38 to 380 l/min)
2 in. (51 mm)	16 to 160 GPM (61 to 610 l/min)

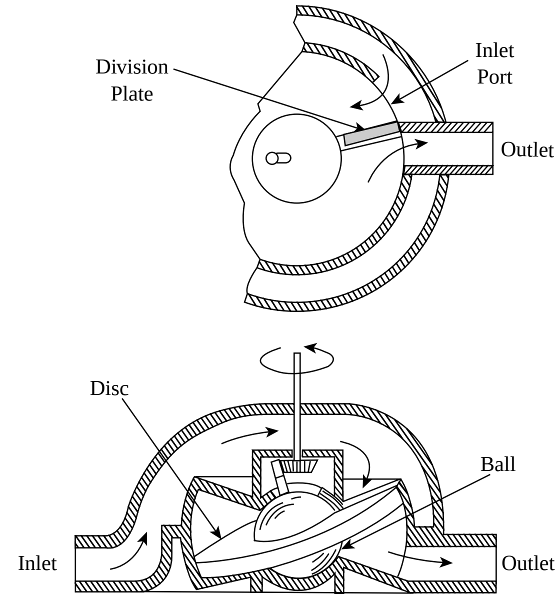

FIG. 2.19c
Nutating disk meter.

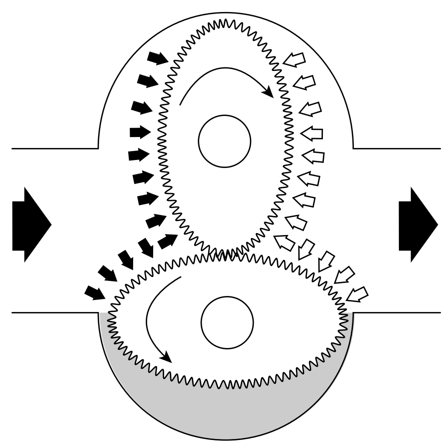

FIG. 2.19d
Oval-gear flowmeter. (Courtesy of Brooks Instrument.)

OVAL-GEAR FLOWMETERS (TYPE C)

A special variety of the rotating-lobe flowmeter is made using oval-geared metering elements. In this design, shown in Figure 2.19d, a precise volume of liquid is captured by a crescent-shaped gap, which is formed between the housing and the gear. This volume is then carried to the outlet, and this movement causes the gears to rotate an output shaft through which the register operates.

In new condition, when the slippage between the oval gears and the housing is small, and when both the flow rate and viscosity are high (>1 GPM and >10 cP, respectively), these flowmeters can operate at errors as low as 0.1% of actual flow. At lower flow rates, the relative proportion of the "slip" leakage increases, and so accuracy drops to about 0.5% of actual flow. Viscosity variations will also affect the slip flow. If a meter was calibrated using water, a fluid with a viscosity of 1 cps, it will have a 1.2% high error if the viscosity rises to 100 cps.

These flowmeters are available in sizes from 0.25 to 16 in. (6 to 406 mm). When the viscosity of the process fluid is between 1.5 and 10 cps, they can handle flow ranges from 0.05 to 0.5 up to 250 to 5000 GPM (from 0.2 to 2 up to 950 to 19,000 l/min). They are available in a wide range of construction materials, including brass, carbon steel, type 316 stainless steel, and Alloy 20®. Operating pressure ratings are available up to 1450 PSIG (10 MPa) and operating temperatures up to 560°F (293°C).

The servo version of this meter has been introduced to completely eliminate slip leakage in smaller sizes (0.2 to 40 GPH or 0.8 to 150 l/h). In this design, the servomotor drives the oval-gear elements at a speed that eliminates the pressure drop across the meter and keeps the outlet pressure the same as the inlet. This eliminates the motivating force, which causes the slip flow and therefore increases accuracy at low flows or under variable viscosity conditions.

A smooth, toothless oval gear design is also available in 1-in. (25-mm) size with screwed connections. It can handle viscosities up to 100 cSt and is rated for 3000 PSIG (21 MPa) and 450°F (232°C). Its linear range is 2 to 25 GPM (7.5 to 94 l/min). If it is used with a nonlinear Hall-effect pickup, its range is claimed to increase to 0.02 to 25 GPM (0.075 to 94 l/min). The meter is made of type 316 stainless steel, its inaccuracy is within its linear range is 0.25% of actual flow, and it is provided with accessories for remote readouts, both analog and digital.

PISTON DESIGNS (TYPE D)

Reciprocating Piston

The oldest of the positive-displacement meters, this meter is available in many forms, including multi-piston meters, double-acting piston meters, rotary valves, and horizontal slide valves. Figure 2.19e shows the schematic of a reciprocating piston meter. Here, a crank arm is operated by the reciprocating motion of the pistons, and this motion drives the register. These meters are widely used in the petroleum industry and can reach the precision of ±0.2% of actual flow.

Another version of this meter is shown in Figure 2.19f. In this design, the liquid enters the cylinder on the left, forcing the piston down by lever action of the control plate. As a result, the piston on the right is forced up, discharging the liquid first into the inner portion of the valve, then down through the center of the meter and out through the meter discharge outlet.

Oscillating Piston

The moving portion of the oscillating piston meter consists of a slotted cylinder that oscillates about a dividing bridge that separates the inlet port from the outlet port. Spokes connect this cylinder to a pin located on the axis of the cylinder. As the cylinder oscillates about the bridge (Figure 2.19g) the pin makes one rotation per cycle. This rotation is transmitted to the gear train and registers either directly or magnetically through a diaphragm. This meter, in addition to being in common usage for the measurement of domestic water has the capability of handling clean viscous and/or corrosive liquids. This type of flowmeter is normally used in smaller pipelines (2 in./50 mm or below) to measure low flow rates.

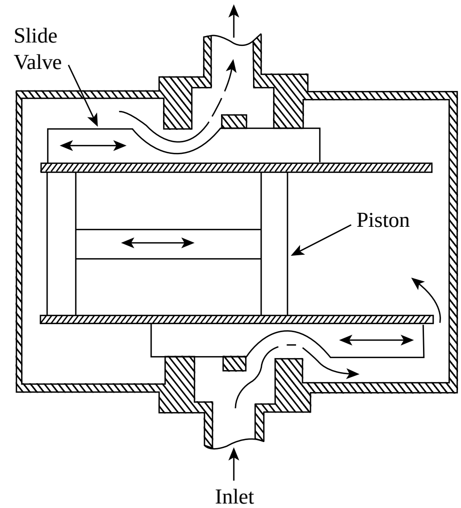

FIG. 2.19e
Reciprocating piston meter.

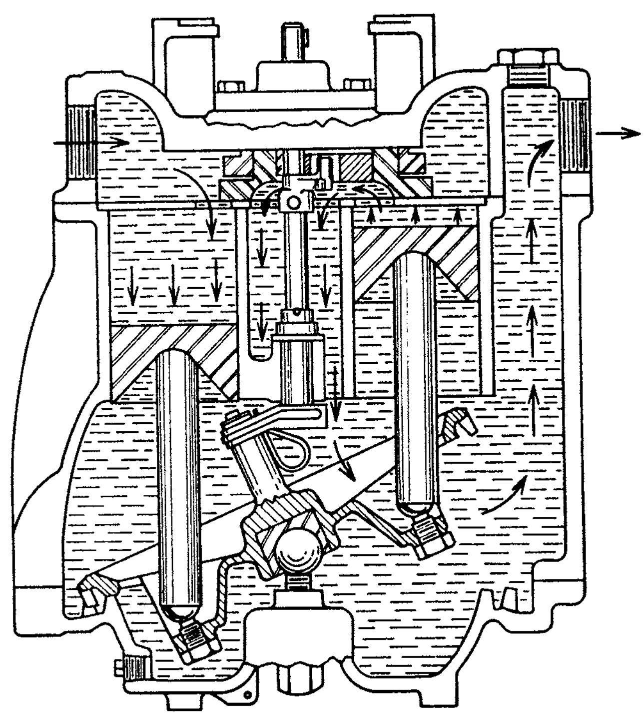

FIG. 2.19f
Cutaway of reciprocating piston meter with two opposing pistons.

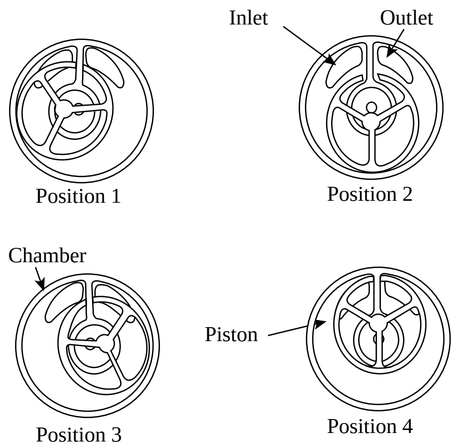

FIG. 2.19g
Oscillating piston meter.

Measurement errors are in the range of ±1% of actual flow. Metering accuracies are increased by reducing the clearance spaces to 0.002 in. (5 microns). Such small clearances do necessitate pre-filtering the entering fluid in order to remove larger particulars. The cases are usually made of cast iron, bronze, or steel, while the chamber and piston materials are usually made of bronze, aluminum, and Ni-Resist. Iron and bronze meters are good for up to 150 PSIG (1034 kPa) and 200°F (93°C), while steel meters can be used up to 400 PSIG (2760 kPa) and 300°F (149°C).

ROTATING VANE (TYPE E)

This flowmeter has spring-loaded vanes that seal increments of liquid between the eccentrically mounted rotor and the casing (Figure 2.19h) and transport it from the inlet to the outlet, where it is discharged as a result of the decreasing volume. This type of meter is widely used in the petroleum industry and is used for such varied services as gasoline and crude oil metering, with ranges from a few gallons per minute of low-viscosity clean liquids to 17,500 GPM (66.1 m^3/m, or 25,000 bbl/h) of viscous particle-laden crude oils. Precisions of ±0.1% of actual flow are normal, and ±0.05% has been achieved in the larger meters.

This instrument is built from a variety of materials and can be used at temperatures and pressures up to 350°F (177°C) and 1000 PSIG (6.9 MPa).

Another rotary design is illustrated in Figure 2.19i. Here, an abutment rotor operates in timed relation with two displacement rotors and at half their speed.

VISCOUS HELIX (TYPE F)

The helix flow transducer (Figure 2.19j) is a positive-displacement device utilizing two uniquely nested, radically pitched helical rotors as the measuring elements. Close machining tolerances ensure minimal slippage and thus high accuracy. The design of the sealing surfaces provides a ratio of longitudinal to lateral sealing to minimize pressure drop, especially with high-viscosity liquids.

The large inlet size of the progressive cavity allows for the passage of gels, fines, agglomerates, and even undissolved

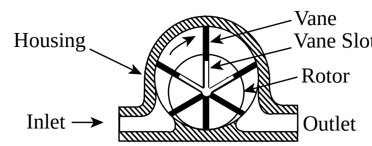

FIG. 2.19h
Rotating-vane meter.

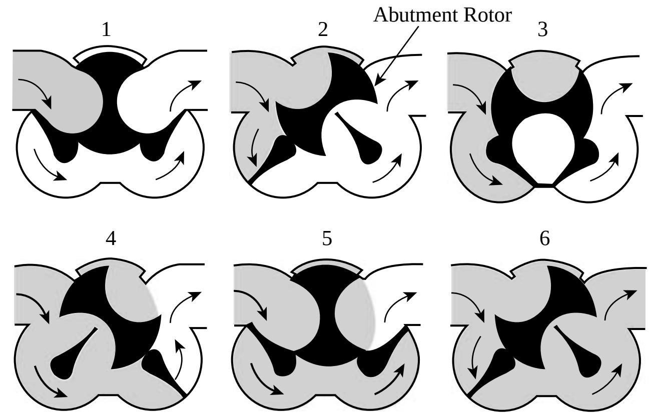

FIG. 2.19i
Six-phase metering cycle of a rotary displacement-type flowmeter.

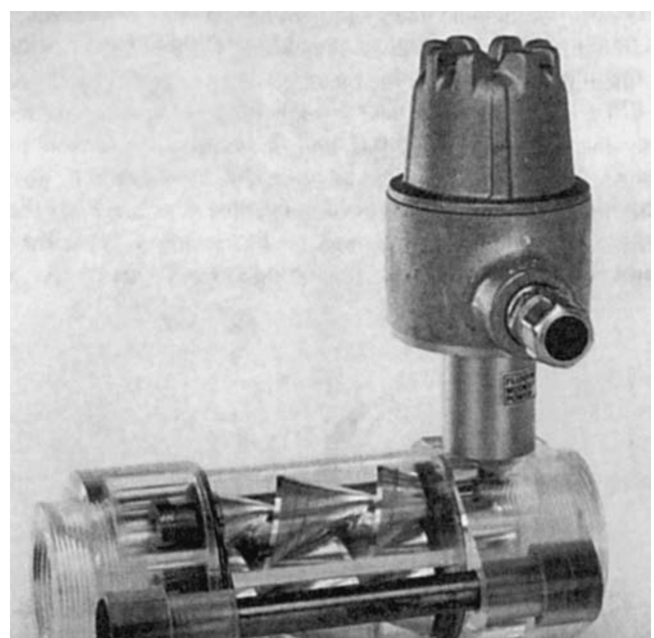

FIG. 2.19j
Viscous helix flowmeter. (Courtesy of Fluidyne Instrumentation.)

or hydraulically conveyed solids. The meter can measure flow rates from 0.5 to >4000 GPM (2 to 15,000 l/min). This flow sensor is available in sizes from 1.5 in. to 10 in. (38 to 250 mm) and can operate at temperatures up to 600°F (315°C) and at pressures up to 3000 PSIG (21 MPa). It is a high-pressure-drop device requiring a minimum of 10 PSID (69 kPa) for its operation at full flow. Its turndown can reach 100:1, and its metering error is claimed to be under 0.5% of actual flow.

Available design variations include versions that are heated to maintain line temperatures for metering melted solids or polymers. Also available are units in sanitary construction. This meter is suited for high-viscosity (over 1000 cps) and for slurry services. The straight-through design with no pockets is also available to simplify cleaning. It is recommended that the process fluids be filtered by mesh size 30 filters before they enter this flowmeter.

HIGH-PRECISION AND SPECIALIZED (TYPE G)

For the high-precision measurement of fuel and alcohol flows in engine and carburetor test rigs and other applications, specialized positive-displacement flowmeters are often used. Their high precision and high rangeability are achieved by eliminating the pressure drop and thereby eliminating the slip or leakage flows. This is achieved by providing a motor drive for the displacement element and using it to introduce as much pumping energy as is needed to equalize the pressures at the inlet and outlet of the meter (Figure 2.19k). This flowmeter uses a high-sensitivity piston to detect the pressure differential and utilizes photoelectric sensors to detect the position of the piston. The flowmeter is also provided with a variable-speed controller, which adjusts the drive speed whenever the pressure differential is other than zero. Because the response time of the system is less than 0.5 sec, the flowmeter is able to follow most dynamic flow transients or can be used on short-duration tests.

This flowmeter is claimed to provide a reading with only 0.25% error over a 50:1 range and a 0.5% error over a 100:1 range. The meter is designed for ambient operating temperatures and for up to 150 PSIG (10 bars) operating pressures.

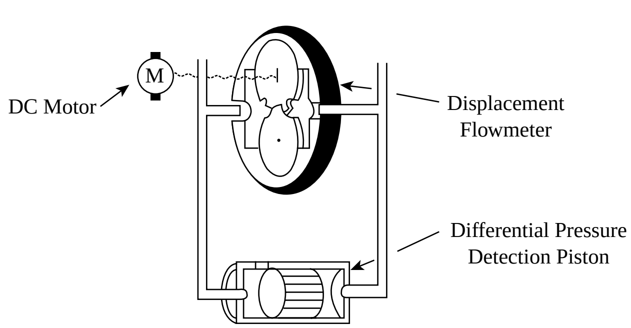

FIG. 2.19k
High-precision positive displacement flowmeter. (Courtesy of PLU, Pierburg GmbH.)

The different models of this flowmeter can detect diesel, gasoline, and alcohol flows from 0.04 to 40 GPH (0.15 to 150 l/h). Because vapor lock is a common problem in fuel flow metering, the unit is provided with a vapor separator.

PROVERS (TYPE H)

All flowmeters that consist of moving and stationary parts that rub against each other (such as positive-displacement and turbine type flowmeters) require periodic recalibration. This is necessary because the clearance space and the slip or clearance flow through that space increase with wear. Recalibration can be done by removing the flowmeter from the pipeline and sending it to a calibration laboratory, or it can be done in line. The flow provers that allow for inline recalibration without interruption of the process flow are described below.

As shown in Figure 2.19l, provers consist of a smooth-walled, precalibrated displacement chamber and a barrier piston within it. Usually, a follower rod is attached to the back side of the piston, which is connected to position sensors. The calibrated flow rate is obtained by dividing the volume of the prover with the time it takes to displace its volume. This calibrated flow rate is then compared to the reading of the flowmeter being calibrated.

To minimize the disturbance to the process flow, inline ballistic flow provers have been developed. In these units (Figure 2.19l), the piston is constructed so that it will not disrupt the flow in the line. Therefore, the prover can be permanently installed in an operating pipeline, upstream or downstream of the flowmeter being calibrated. The poppet valve within the piston assembly allows for the piston to be withdrawn to the start position after a calibration run while the process flow continues undisturbed. Both portable (Figure 2.19m) and permanently installed provers are available, and the calibration can be manual or automatic.

The repeatability of provers is around 0.02% of the actual flow if the seals are tight. It is recommended to periodically check the seals by closing a tight shutoff valve downstream of the prover and applying nitrogen pressure to the upstream

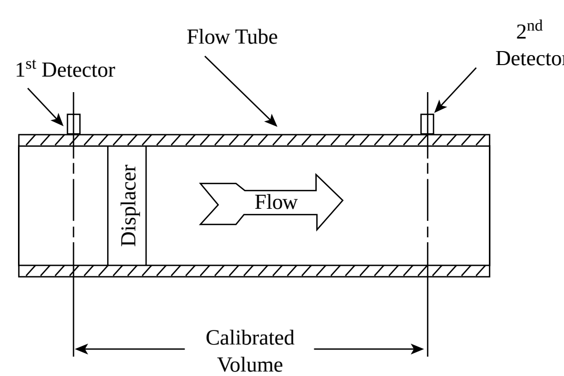

FIG. 2.19l
Prover operation.

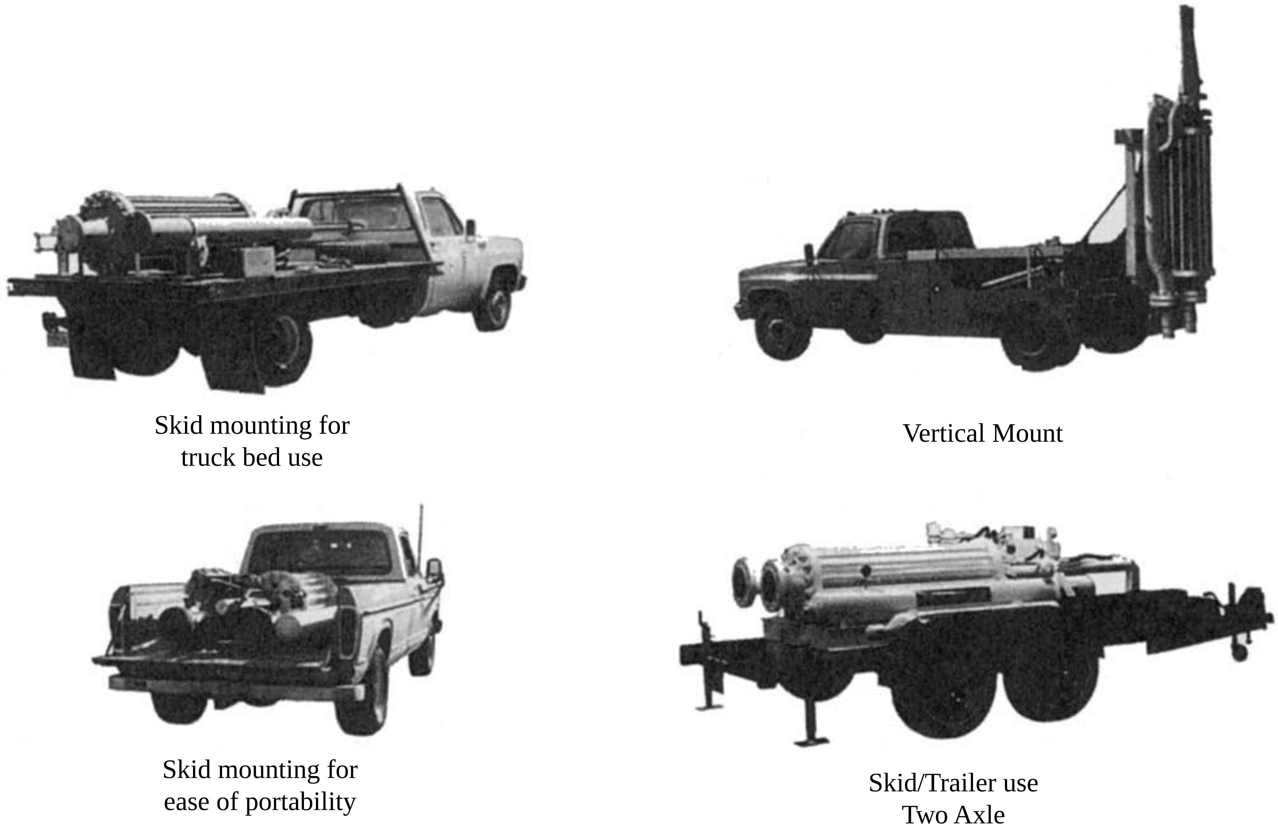

FIG. 2.19m
Portable prover assemblies. (Courtesy of Brooks Instrument.)

face of the piston. If this results in any movement of the piston, the seals need maintenance. Provers are available for up to 3000 PSIG (21 MPa) operating pressure and 165°F (74°C) operating temperature; they can detect flow rates from 0.001 GPM (0.004 l/min) to 20,000 GPM (75,000 l/min). The calibrated displacement volume of provers can range from a fraction of a gallon to several hundred gallons. Large provers can fit on truck beds or trailers (Figure 2.19m).

ACCESSORIES AND INTELLIGENT ELECTRONICS

Standard accessories for positive-displacement include strainers; air release assemblies, which remove all the vapors from the flow stream before it enters the meter; automatic batch shutoff valves, which provide two-stage closure for full and dribble flow operation; temperature compensators; manual and/or automatic ticket printers; and pulse generators for remote indication, totalization, and other forms of data monitoring and/or control. In addition to the totalizer-type digital readout registers, flow rate indication can also be provided. Impulse contactors are also available to actuate predetermining counters or to serve as electrical interlocks that actuate flow ratio systems, pumps, valves, solenoids, alarms, printers, sampling devices, and so on. Pneumatic pulse generators are still available and sometime used in explosion-proof areas for interfacing with pneumatic batch controllers.

The intelligent positive-displacement meters are usually provided with magnetic or Hall-effect-type pickup and frequency outputs from solid-state pulse transmitters. The frequency outputs can be sent to central computers or DCS/PLC systems over the data highways and can also be converted to 0- to 10-VDC or 4- to 20-mA analog signals.

In household utility applications, there is substantial economic justification for substituting a telemetering system, operated either on the telephone lines or by radio, replacing the current system (human meter readers). It is also feasible to combine the readings of electric, water, and gas meters of a household into a single transmitter and to transmit that information to the appropriate utilities without the need for a meter reader to visit the home or apartment. The economic advantages of this type of metering is not only in labor savings but also in the speed and frequency at which the data can be obtained and used for billing or other purposes.

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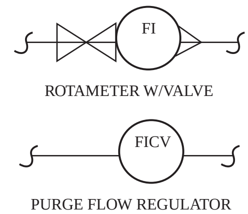
2.20 Purge Flow Regulators

E. L. SZONNTAGH (1995) **B. G. LIPTÁK** (2003)



Flow Sheet Symbol

Applications	Purge flow regulators serve the regulation of low flow rates of air, gas, or liquids. They are most often used in air bubblers or in purging electrical housings (in explosion-proof areas) and in purging optical windows of smokestack analyzers. Water and liquid purge meters are most often applied to protect process connections from plugging.
Purge Fluids	Air, nitrogen, and liquids
Operating Pressure	Up to 450 PSIG (3 MPa)
Operating Temperature	For glass tube, up to 200°F (93°C)
Ranges	Range is from a minimum of 0.01 cm^3/min for liquids and from 0.5 cm^3/min for gases. A 0.25-in. (6-mm) glass tube rotameter can handle 0.05 to 0.5 GPM (0.2 to 2 l/min) of water or 0.2 to 2 SCFM (0.3 to 3 cmph) of air.
Inaccuracy	Generally, 2 to 5% of range (laboratory units are more accurate)
Costs	A 150-mm glass-tube unit with 0.125-in. (3-mm) threaded connection, in type 316 stainless steel, and a 16-turn high-precision valve will cost about $300; the same with an aluminum frame and a standard valve is about $125. Adding a differential-pressure regulator of brass or aluminum construction costs about an additional $150 (in stainless steel, about $500). For highly corrosive services, all-Teflon®, all-PTFE, all-PFA, and all-CTFA units are available that, when provided with valves, cost from $500 with 0.25-in. (6-mm) to $1500 with 0.75-in. (19-mm) connections.
Partial List of Suppliers	Aalborg Instruments & Controls Inc. (www.aalborg.com) ABB Automation Instrumentation Division (www.abb.com/us/instrumentation) Blue-White Industries (www.bluwhite.com) Brooks Instrument (www.emersonprocess.com) Cole-Parmer Instrument Co. (www.coleparmer.com) Dwyer Instruments Inc. (www.dwyer-inst.com) Key Instruments (www.keyinstruments.com) King Instrument Co. (www.kinginstrument.co.com) Krohne Inc. (www.krohne.com) Matheson Instruments (www.mathesoinstruments.com) Omega Engineering Inc. (www.omega.com) Penberthy (www.penberthy-online.com) USFilter/Wallace & Tiernan Products (www.wallaceandtiernan.usfilter.com)

Purge flows are low flow rates of either gases or liquids. They serve to protect pressure taps from plugging or being contacted by hot or corrosive process fluids. Inert gas purging can also serve to protect electrical devices from becoming ignition sources by maintaining a positive pressure of incombustible gases inside their housings. In the case of analyzers, purging protects the cleanliness of the optics.

DETECTION OF LOW FLOWS

The low flow rates of purge media can be detected by a variety of devices. They include capillaries, miniature orifices, metering pump, positive-displacement, thermal, and variable-area-type flow sensors. Most of these devices are detailed in other sections of this chapter. Capillary flow elements (Section 2.9) are ideal for the measurement of low flow rates. They can also be combined with thermal flowmeters to provide flow regulators with higher precision and higher rangeability—but also higher cost (Section 2.13). Integral orifices (Section 2.15) can also be used in both gas and liquid flow measurement, whereas positive-displacement meters and metering pumps are most often used to detect the flows of liquids (Sections 2.14 and 2.19). In addition, the second volume of the *Instruments Engineers' Handbook* ("Process Control") includes a section that describes self-contained flow regulators.

Only one purge flow regulator design is not covered in other parts of this three-volume handbook: the rotameter-type purge meter. This is the least expensive and most widely used purge meter design, and it is described in this section.

PURGE ROTAMETERS

Purge flowmeters are widely used devices and are probably the most widely used form of the variable-area flowmeter, the rotameter. These meters are inexpensive and are intended for the measurement and control of low flow rates. Most purge meters are used on inert gas or water services at low flow rates, where measurement accuracy is not critical. These units are reasonably repeatable, which is all that is required in many purge applications where, as long as a low flow rate is maintained, it is not critical to know how much it is. The flow rates through the purge meters are adjusted by needle-type throttling valves as shown in Figure 2.20a.

The metering needle valves are usually multiple-turn units provided with long stems. The opening around their needle-shaped plugs is very small and can approach capillary dimensions. Figure 2.20b shows a high-precision needle valve provided with a vernier-type scale that allows a more accurate setting of the valve opening. The dual scale increases the precision and reproducibility of setting by subdividing the smallest reading of the first scale onto the second. The flow rate through these devices is a function of the opening in the valve, the pressure differential across that opening, and both the density and the viscosity of the purge media. Table 2.20c provides information on the density and viscosity of a number of purge gases.

When the purge flowmeter is combined with a differential-pressure regulator (Figure 2.20d), it becomes a self-contained flow controller. The purge flow is fixed by adjusting springs 1 and 2 for a particular pressure difference, usually in the range of about 60 to 80 in. (150 to 200 cm) of water. This constant pressure drop ($P_2 - P_o$) is than maintained across

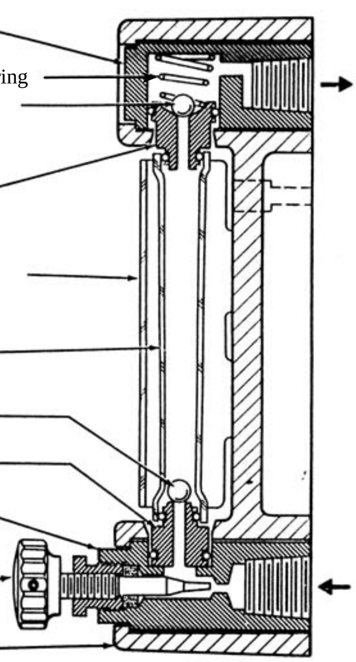


FIG. 2.20a
Purge rotameter with integral needle valve.

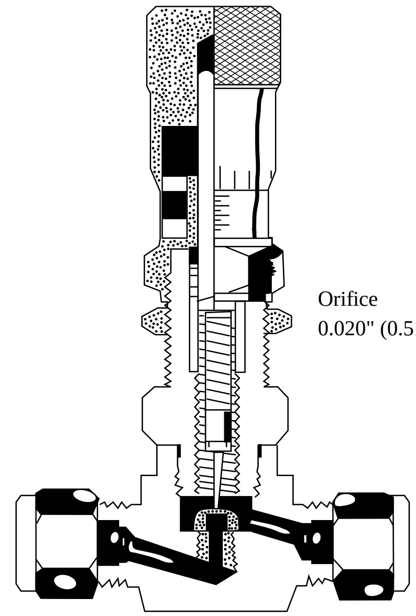


FIG. 2.20b
Fine-adjustment needle valve with vernier scale. (Courtesy of Swagelok Co.)

TABLE 2.20c
Gas Properties under the Standard Conditions of 29.92 in. of Mercury and 70°F (760 mm of Mercury and 21°C)

Gas	*Density (lb/ft^3)*	*μ Viscosity Micropoises*	*Specific Gravity*
Air	0.0749	181.87	1.000
Argon	0.1034	225.95	1.380
Helium	0.0103	193.9	0.138
Hydrogen	0.0052	88.41	0.0695
Nitrogen	0.0725	175.85	0.968
Oxygen	0.0828	203.47	1.105
Carbon Dioxide	0.1143	146.87	1.526

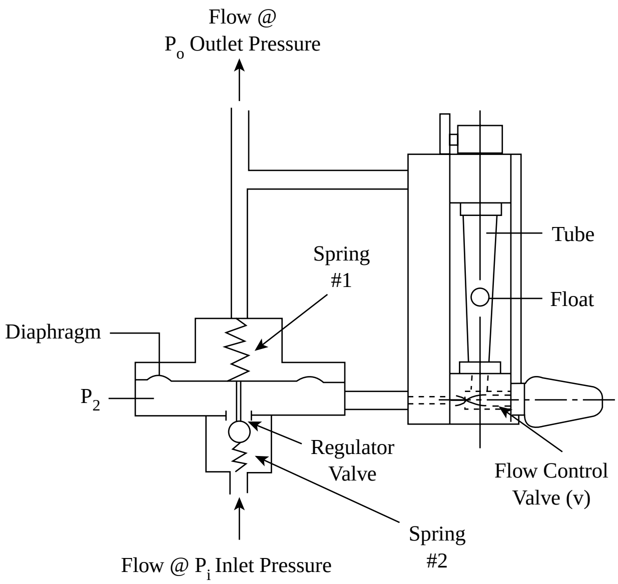


FIG. 2.20d
Purge flow regulator consisting of a glass tube rotameter, an inlet needle valve, and a differential pressure regulator. (Courtesy of Krone Inc.)

the flow control valve (V). The configuration in Figure 2.20d maintains the outlet pressure (P_o) constant by compensating for any variation in the inlet pressure P_i by changing the regulator valve opening.

Other purge flowmeter designs are also available that work in a reverse configuration by keeping the inlet pressure P_i constant and allowing the outlet P_o to vary. In these designs, the constant pressure drop across the valve (V) is maintained to equal ($P_i - P_2$) instead of ($P_2 - P_o$) being kept constant. The gas flows through purge flow controllers are usually adjustable in a range of 0.2 to 2 SCFH (6 to 60 slph). The error or inaccuracy is usually 5% of full scale over a range of 10:1. The standard pressure and temperature ratings are 150 to 300 PSIG (1 to 2 MPa) and 212 to 572°F (100 to 300°C).

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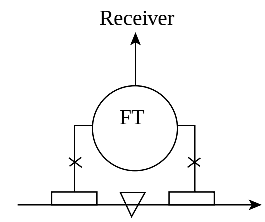
2.21 Segmental Wedge Flowmeter

B. G. LIPTÁK (1995, 2003)



Flow Sheet Symbol

Applications	Clean, viscous (down to Rd no. = 500) solids containing fluids, gas, and steam
Sizes	0.5- to 24-in. (12- to 610-mm) diameter pipes
Designs	In the smaller sizes (0.5 to 1.5 in.), the wedge can be integral; for larger pipes, remote seal wedges are used with calibrated elements
Wedge Opening Height (H)	From 0.2 to 0.7 of pipe inside diameter
Pressure Drops	25 to 200 in. H_2O (6.2 to 49.8 kPa)
Materials of Construction	Carbon, type 316 SS, Hastelloy®, Monel® wetted parts; special wedge materials like tungsten carbide are also available. Sealing gasket can be silicate ceramic filled TFE. Chemical tee gasket up to 645°F (340°C) can be graphite.
Design Pressure	300 to 1500 PSIG (20.7 to 103 bars) with remote seals, up to 3000 PSIG (21,000 kPa) in 1-in. size and below
Design Temperature	In sizes 1.5 in. and below, 300°F (148.9°C); higher temperature designs are available from –40 to 700°F (–40 to 370°C) but have been used in higher-temperature processes up to 850°F (454°C).
Inaccuracy	Error, if uncalibrated, is 5% of actual flow. When the elements are individually calibrated, the error drops to 0.5 to 0.75% of actual flow; to this one should add the d/p cell error contribution of about 0.25% of full scale. The total error over a 3:1 flow range is usually not more than 2% of actual flow
Cost	A 3-in. (75-mm) calibrated stainless-steel element with two stainless chemical tees and with an electronic d/p transmitter provided, and provided with remote seals, is about $4000.
Partial List of Suppliers	ABB Automation Instrumentation Division (www.abb.com/us/instrumentation)

The shape of the flow opening of a segmental wedge flowmeter is similar to that of a segmental orifice except that the obstruction to flow is less abrupt (more gradual). Also, the sloping entrance somewhat resembles the shape of the various flow tubes.

The wedge flowmeter was primarily designed for slurry applications. Its main advantage is its ability to operate at Reynolds numbers as low as 500 to 1000.[1] This is in contrast with sharp-edged orifices, venturies, and flow nozzles, where the square root relationship between flow and pressure drop requires a Reynolds number well above 10,000 (see Figure 2.1f). For this reason, wedge flowmeters can measure low-velocity and viscous fluid flows. In this regard, the wedge flowmeter capability is similar to that of the conical or quadrant edge orifices.

For pipe diameter sizes under 2 in. (50 mm), the segmental wedge flow element is made by cutting a V-notch into the pipe and accurately welding a solid wedge in place. In sizes over 2 in., the wedge is fabricated from two flat plates that are welded together before insertion into the spoolpiece (Figure 2.21a). On clean services, regular pressure taps are used and located equidistant from the wedge (Figure 2.21a). On viscous or dirty services, or on applications where the process fluid contains solids in suspension, "chemical tees" are installed upstream and downstream of the wedge flow element (Figure 2.21b).

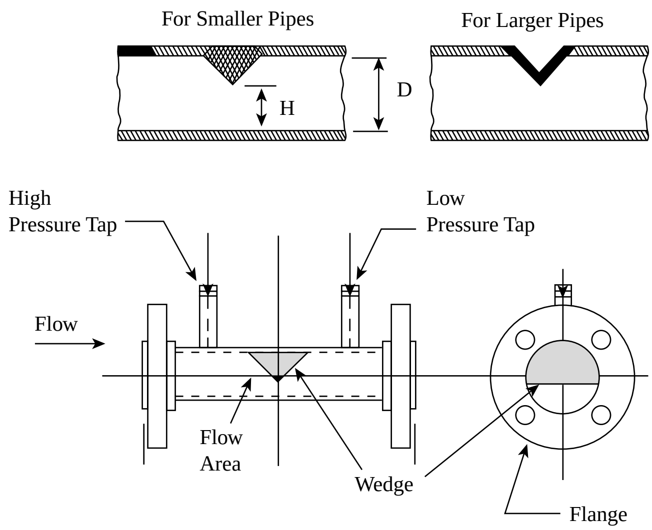


FIG. 2.21a
The segmental flowmeter designed for clean fluid service.[1,2]

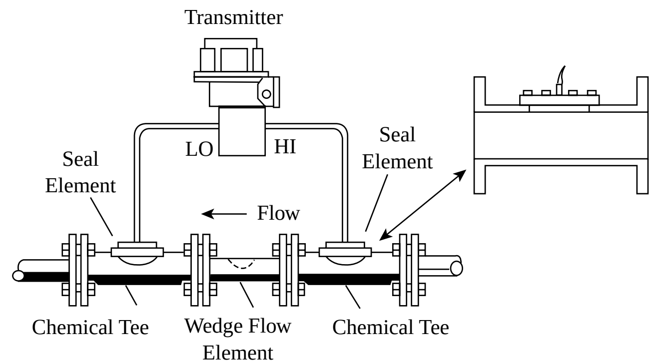


FIG. 2.21b
Segmental wedge flowmeter designed for corrosive or slurry service.[1]

TABLE 2.21c
Segmental Wedge Flowmeter Capacities in GPM Units (Courtesy of ABB Instruments – previously ABB Kent-Taylor)*

		Approximate Differential Pressure Inches H_2O					
Pipe Size	*H/D*†	*20 in.*	*40 in.*	*60 in.*	*100 in.*	*120 in.*	*160 in.*
1 in.	0.2	3.43	4.80	5.90	7.66	8.40	9.70
	0.3	5.75	8.14	9.95	12.9	14.1	16.3
	0.4	8.30	11.7	14.4	18.6	20.4	23.4
	0.5	11.0	15.6	19.1	24.6	27.0	31.2
1–1/4 in.	0.2	6.80	9.70	11.9	15.8	16.8	19.4
	0.3	12.8	18.2	22.2	28.7	31.4	36.4
	0.4	22.7	32.1	39.3	50.7	55.5	64.2
	0.5	32.2	45.5	55.8	72.0	79.0	91.0
2 in.	0.2	12.2	17.2	21.1	27.2	29.9	34.6
	0.3	20.3	28.7	35.2	45.4	49.7	57.5
	0.4	34.0	48.0	58.9	76.0	83.4	96.3
	0.5	50.9	72.0	88.0	114.0	125.0	144.0
3 in.	0.2	26.4	37.4	45.6	59.0	64.6	74.6
	0.3	44.5	62.5	77.0	99.5	109.0	126.0
	0.4	75.5	107.0	131.0	169.0	185.0	214.0
	0.5	113.0	160.0	196.0	252.0	277.0	320.0
4 in.	0.2	49.5	70.0	86.0	111.0	121.0	140.0
	0.3	76.1	108.0	132.0	170.0	187.0	216.0
	0.4	127.0	180.0	220.0	284.0	311.0	360.0
	0.5	192.0	272.0	332.0	430.0	470.0	544.0
6 in.	0.2	86.4	122.0	150.0	193.0	212.0	244.0
	0.3	185.0	262.0	320.0	414.0	454.0	524.0
	0.4	294.0	416.0	509.0	657.0	720.0	831.0
	0.5	444.0	628.0	768.0	994.0	1089.0	1255.0
8 in.	0.2	173.0	244.0	300.0	388.0	425.0	490.0
	0.3	311.0	440.0	539.0	695.0	761.0	880.0
	0.4	475.0	671.0	824.0	1060.0	1165.0	1340.0
	0.5	659.0	930.0	1140.0	1470.0	1610.0	1860.0

*The units in the table can be converted as follows: 1.0 in. H_2O = 249 Pa, 1.0 GPM = 3.785 lpm, 1.0 inch = 25.4 mm.
†The H/D values shown above represent ratios between segmental opening height and the pipe diameter (Fig. 2.21a).

On these tees, chemical seal elements are installed flush with the pipe, eliminating pockets and making the installation self-cleaning. The seals are usually made of corrosion-resistant materials and are also suited for high-temperature services. Some applications have been reported in which the operating conditions reached 3000 PSIG (210 bars) and 850°F (454°C).[2]

The segmental wedge flowmeters are usually calibrated on water. The pressure drop detected by d/p transmitter is interpreted on the basis of these calibration curves. The measurement error is a function of the precision of the calibration and some users report performance on slurry service within 2.5 and 3.5% of actual flow.[2] The flow capacities of these sensors are listed in Table 2.21c.

Based on the above, one might conclude that the segmental wedge flowmeter fills the need for corrosion-resistant slurry flowmeters that are capable of operating at high process pressures and temperatures, but only if the accuracy and rangeability requirements for the measurement are not high.

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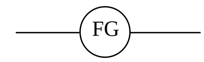
2.22 Sight Flow Indicators



Flow Sheet Symbol

D. S. KAYSER (1982) **B. G. LIPTÁK** (1995) **G. G. SANDERS** (2003)

Design Pressure	To ANSI 600# standard (≈1400 PSIG [9.6 MPaG] material dependent)
Design Temperature	To 500°F (260°C) standard
*Materials of Construction**	Windows: soda-lime glass, tempered or annealed borosilicate glass, aluminosilicate glass, quartz, polycarbonate, acrylic Body: bronze, iron, carbon steel, stainless steel, duplex steel, Monel®, Hastelloy®, Alloy 20® Cb-3, and so forth Gasketing: Buna-N, Viton®A, Neoprene®, polyethylene, polypropylene, PTFE, graphite, fibrous, PTFE sandwiched fibrous, and so on
Sizes	0.25 to 16 in. NPS/BSP/DIN/JIS
Cost	A 0.25-in. NPS bronze/brass unit with PTFE rotator is $175; 1-in. NPS all-stainless, screwed unit is $440, with flanged connections, $600
Partial List of Suppliers	Archon Industries Inc. (www.archonind.com) Brooks Instrument Div. of Emerson (www.emersonprocess.com) Dwyer Instruments Inc. (www.dwyer-inst.com) Eugene Ernst Products Co. (www.eepproducts.com) John C. Ernst Co. (www.johnernst.com) ERDCO Engineering Corp. (www.erdco.com) Jacoby Tarbox (www.clark-reliance.com) The Johnson Corp. (www.joco.com) Kenco Engineering (www.kenco-eng.com) Kobold Instruments Inc. (www.koboldusa.com) OPW Engineered Systems (www.opw-es.com) J. G. Papailias Co. (www.papailias.com) Penberthy-Tyco Valves and Controls LP (www.tycovalves.com) Plast-O-Matic Valves Inc. (www.plastomatic.com) Pressure Products Company Inc. (www.pressureproducts.com) Schutte and Koerting (www.s-k.com) L.J. Star Inc. (www.ljstar.com) Tokheim Corp. (www.tokheim.com)

Sight flow indicators (SFIs, a.k.a. flow glasses) provide a window into a pipe when visual inspection of a process fluid is necessary. Figure 2.22a shows five standard designs.

DESIGN VARIATIONS

The plain design is used to observe physical characteristics of the process fluid; it is not meant to provide full pipe flow indication. Four types of indicating devices are incorporated when flow indication is desired. A metallic flapper design is used in transparent or slightly opaque liquids, and a lightweight polymer/glass flapper is for low-flow gaseous service. Flow direction must be vertically upward or horizontal. Some indication of relative flow velocity can be made by observing the angular position of the flapper; some manufacturers place decals on the window that approximate flow quantity (based on impact force × area) (Figure 2.22b). Bidirectional flappers are hinged in the center of the SFI body

* Registered trademarks of Inco Alloys International Inc., Hayes International Inc., Carpenter Technology Corp., and E.I. du Pont de Nemours & Co. are noted by ®.

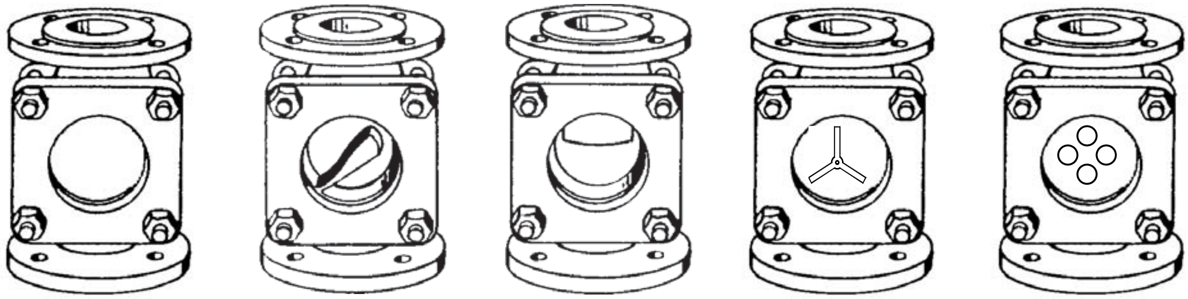


FIG. 2.22a
Basic sight flow indicator and four types of flow indicators.

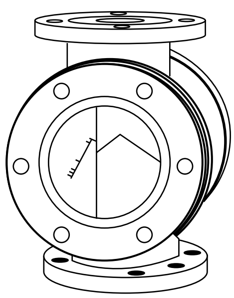


FIG. 2.22b
Flapper-type sight glass provided with a scale for approximation of flow.

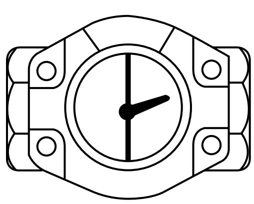


FIG. 2.22c
Bidirectional flapper. (Courtesy of Dover Corp., OPW Div.)

(Figure 2.22c) for horizontal use only. The drip-tube design is used for intermittent or extremely slow flows such as distillation; flow direction should be vertically downward or horizontal. The rotator (a.k.a., propeller, paddle, or paddle-wheel, usually made of white virgin PTFE) is used with dark or opaque process fluids. The rotator is placed close to the window, and its motion is easily detected. Flow through the rotator design may be in any orientation. Very high flow rates will rapidly destroy a rotator, so it is advisable to oversize the SFI (to reduce flow velocity) or use a different indicator if high flow rates are likely. Caged balls provide an indicator that is more sensitive to low flow than the flapper and will withstand high flow velocities that would destroy a rotator. All indication devices have a minimum flow velocity for first indication. The rotator-style indicator creates relatively high pressure drops (almost an order of magnitude greater than other indicators) due to internal flow redirection required for operation (Figure 2.22d).

Figure 2.22e shows the cross section of a typical flanged sight flow indicator. The assembly consists of the body, glasses, sealing and cushion gaskets, covers, and bolting. It is similar in many respects to the transparent level gauge discussed in Chapter 3. Soda-lime glass (like window panes) should be considered only for nonsevere applications. Standard industrial glass is borosilicate, rated to 500°F (260°C) for flow glass applications. It has good resistance to mechanical and thermal shock. For higher temperatures, special glass must be specified such as aluminosilicate, up to 800°F (425°C); fused silica or quartz allows ratings in excess of 1000°F (535°C). Tempered glass is not recommended for fluorine, hydrofluoric acid, or phosphoric anhydride service, because corrosion causes uneven stresses and eventual failure. Annealed glass is a better choice, because it signals the approach of failure by turning cloudy. To reduce point compression stress on the glass, a design is available that forms glass inside a metallic compression ring. Bolting stresses are applied to the metallic ring, not to the glass. For steam service, mica shields help protect the glass from corrosion; for fluoride/phosphoric or caustic service, consider PCTFE shields. Polymer-coated glass is also available. Polycarbonate (PC) can be used instead of glass. Acrylic (PMMA) may be used if high impact strength and abuse resistance is required, but acrylic scratches easily.

Polymer bodies are available for low pressure, near ambient temperature applications. SFI bodies may be obtained in almost any castable alloy. Metallic bodies can be lined with a variety of polymers enabling a properly specified SFI to be used in almost any corrosive service. Use caution when specifying a lining if the SFI is used in vacuum service; not all lining materials are adherent. The non-wetted bolting and covers are normally steel but may be obtained in different materials depending on anti-corrosion and temperature requirements.

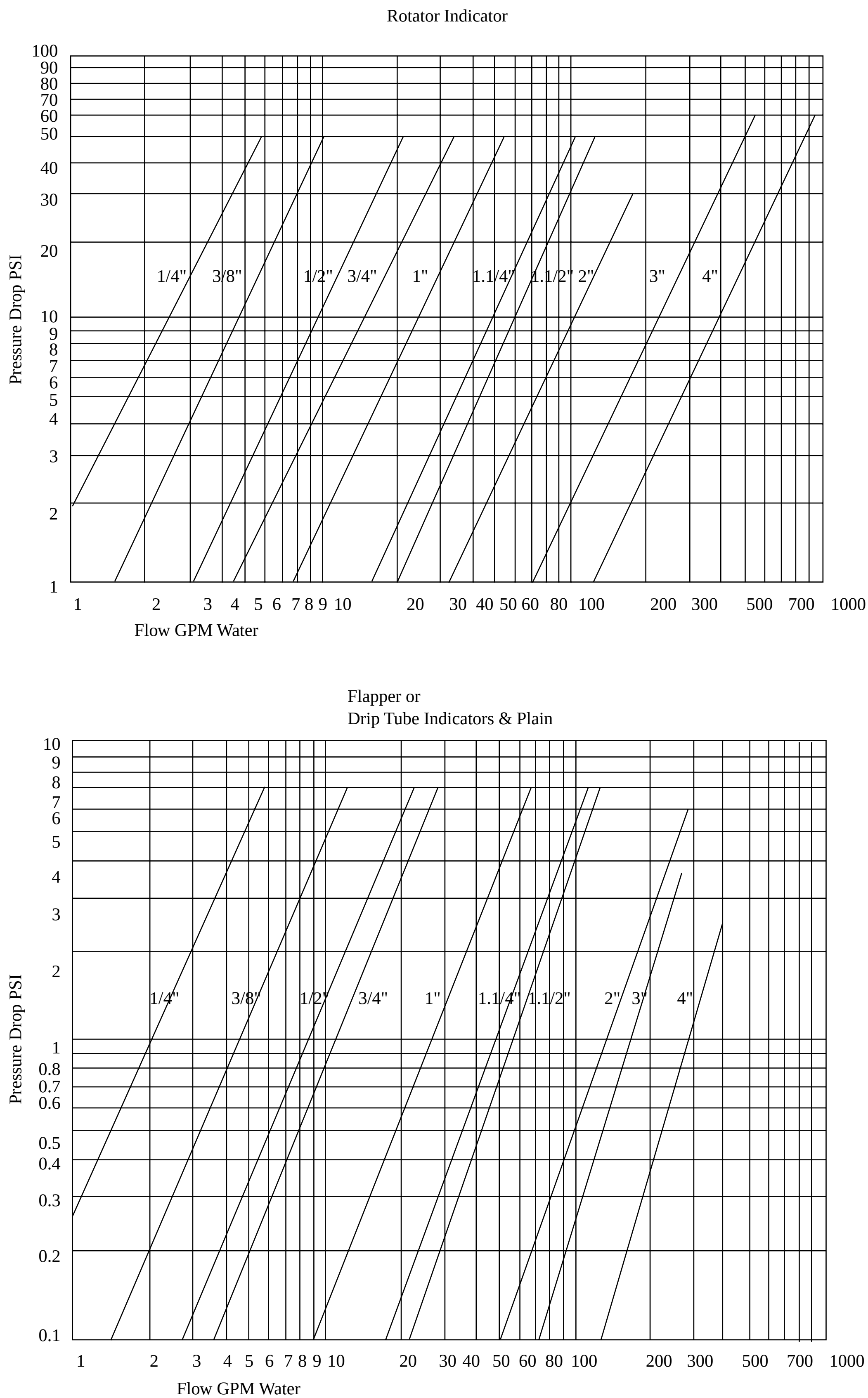


FIG. 2.22d
Sight flow indicator pressure drops on water application. (Courtesy of Dover Corp., OPW Div.)

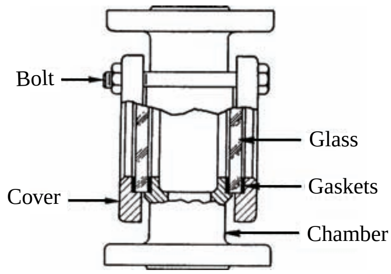


FIG. 2.22e
Cross-section of sight flow indicator.

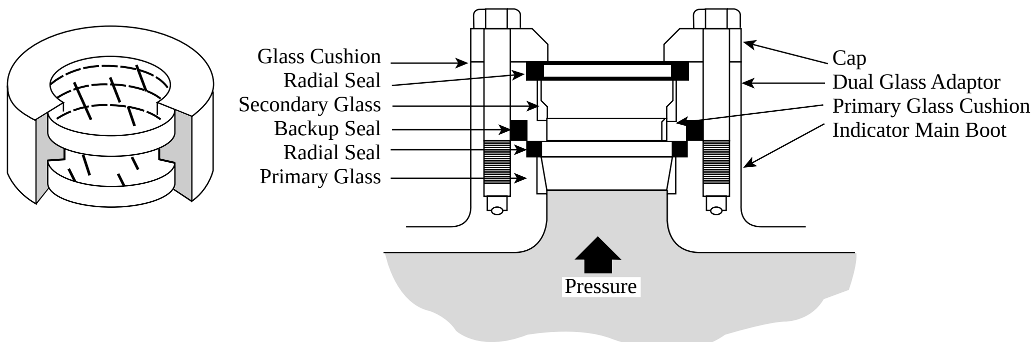


FIG. 2.22f
Cross-section of a dual window assembly. (Courtesy of Dover Corp., OPW Div.)

DUAL-WINDOW AND FULL-VIEW DESIGNS

Figure 2.22f shows the cross section of a dual-window assembly. This assembly improves the safety of an SFI in two ways. In high-temperature service, the thermal gradient across each glass is reduced, and the outer glass protects the inner glass from thermal shock caused by splashes of cold water, e.g., slant rain or snow. If the outer or inner glass breaks, there is a chance that the remaining glass may contain the process until the assembly can be repaired. Dual-window SFIs may be ordered with third-party safety approvals. To further enhance safety due to abuse or vandalism, or if the process fluid is hazardous or toxic, protective sheaths are recommended on either standard or dual-window SFIs.

In smaller pipe sizes, pressure ratings are available up to 3000 PSIG (20.6 MPa). Gasketing may be any available type except those that would cause pressure risers on the glass (e.g., graphite with tanged stainless-steel inserts). Final SFI pressure and temperature ratings may depend on the gasketing material selection. Special designs are available that can be used in sanitary services such as food/pharmaceutical processing. Available accessories include safety jackets, illuminators, insulation blankets, and spray nozzles/rings and wiper blades for cleaning the glass in place.

Most SFI bodies are designed for the inclusion of instrumentation taps, e.g., thermowells. Several types of process analyzers require plain flow glass so the operator can see the probe or other sensing element in the process. Instrumentation using visible, IR, or UV light has been adapted to SFIs using attenuation or backscatter to noninvasively monitor chemical processes. Elbow-style SFIs, both 45 and 90° (Figure 2.22g), have tapping bands available to allow use as elbow differential-pressure flowmeters.

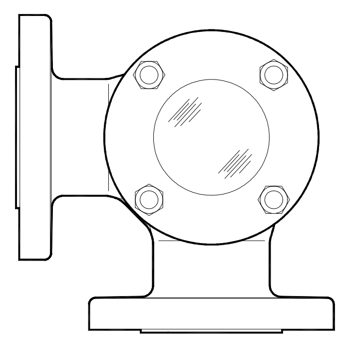


FIG. 2.22g
90° elbow sight flow indicator.

Standard SFI bodies are made with a cross-sectional area expansion from piping bore to accommodate full-bore-size vision. If minimum flow profile distortion is desired, full view SFIs (Figure 2.22h) are designed to maintain piping bore diameter. These are essentially constructed of a spoolpiece with tubular glass either radially or end compression sealed forming the body. They are available plain (360° viewing) or in an armored version for breakage protection, but the armoring reduces visibility. These are normally used for vertically upward flow and are available flanged or threaded.

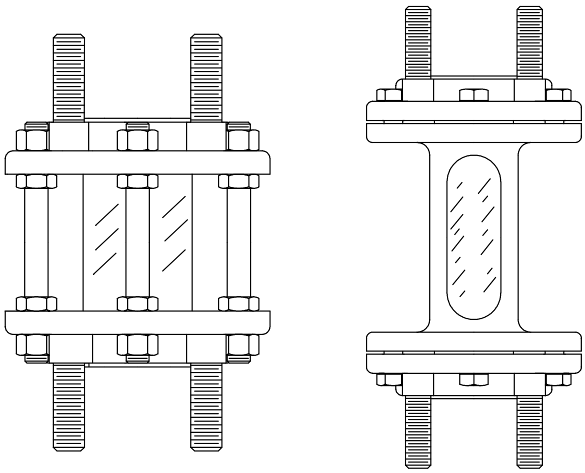


FIG. 2.22h
Flanged full view and armored full view SFI.

A variation of the standard SFI called a sight window (Figure 2.22i) is one window face of an SFI with either flanged or threaded connections designed to fit a piping tee or coupling.

CONCLUSION

Sight flow indicators offer an inexpensive means of viewing process material inside a pipe to detect flow or to note process characteristics such as color, turbidity, or other properties that might indicate process deterioration or equipment malfunction. SFIs are also used in secondary services such as condensate pot installations.

Nonetheless, SFI use is limited to primary industrial process areas, because it is difficult to estimate flow rate through a flow glass, and a hazard is created if the glass breaks. They are more commonly used in utility services associated with industrial processing.

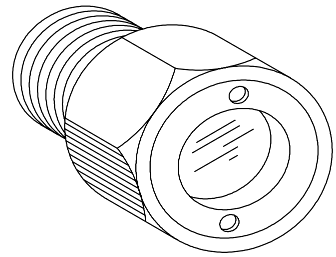


FIG. 2.22i
Threaded sight window.

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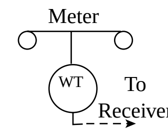
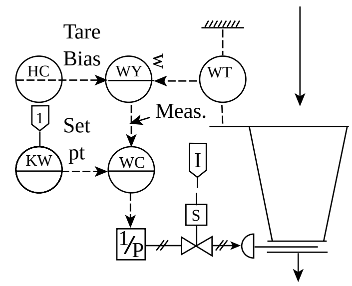
Sunderhous, C. A., Sight indicators allow positive flow check, *Machine Design,* October 1985.

2.23 Solids Flowmeters and Feeders

R. SIEV (1969) **D. C. MAIR** (1982) **B. G. LIPTÁK** (1995, 2003)



Belt Type



Loss in Weight

Flow Sheet Symbols

Types of Designs

A. Accelerator
B. Belt-type gravimetric
C. Volumetric, capacitance
D. Impulse or impact
E. Loss-in-weight
F. Switch (Section 2.7)
G. Dual-chamber
H. Cross-correlation (Section 2.5)
I. Nuclear
J. Microwave

Capacities

A. 1000 to 80,000 lbm/h (450 to 36,000 kgm/h)
B. Up to 180,000 lbm/h (80,000 kgm/h) or up to 3600 ft^3/h (100 m^3/h)
C. Up to 3600 ft^3/h (100 m^3/h)
D. 3000 to 3,000,000 lbm/h (1400 to 1,400,000 kgm/h)
E. Determined by hopper or duct size
F. Unlimited on–off
G. 1000 to 300,000 lbm/h (450 to 140,000 kgm/h)
H. Unlimited
I. Same as B
J. Unlimited on pulverized coal applications

Costs

\$1000 to \$2000 (F)
Around \$4000 (C)
\$4000 to \$6000 (A, D)
\$5000 to \$20,000 (B, H)
\$15,000 to \$30,000 (E, G, I)

Inaccuracy

±0.5% of rate over 10:1 range (B [digital], G)
±0.5% to ±1% of full scale (I)
±1% of rate over 10:1 range (E)
±1 to ±2% of full scale (D)
±2 to ±3% of full scale (A, F)
±2 to 4% of full scale (C)

Partial List of Suppliers

ABB (www.abb.com) (C).

Air Monitor Corp. (www.airmonitor.com) (J)
Babbitt International Inc. (www.babbittlevel.com) (D)
Cardinal Scale Mfg. (www.ardinalscale.com) (B)
Cutler-Hammer, Thayer Scale Div. (www.cutlerhammer.eatoncom) (B, D, E)
DeZurik/Copes–Vulcan, a Unit of SPX Corp. (www.dezurikcopesvulcan.com) (A)
Endress+Hauser Inc. (www.us.endress.com) (B, C, D, F, H)
Fairbanks Scales (www.fairbanks.com) (B)
ICS Advent (www.icsadvent.com) (E)
Kay-Ray/Sensall (www.thermo.com) (I)
Kistler-Morse Corp. (www.kistlermorse.com) (B)
M-System (www.m-system.com) (B)
Milltronics Inc. (www.milltronics.com) (B, D)
Monitor Technologies LLC (www.monitortech.com) (F)
Ohmart/VEGA (www.ohmartvega.com) (I)
Technicon Industrial Systems (www.technicon.com) (G)

Many types of solids flowmeters are currently available. The majority depend on some method of weighing, but others utilize a variety of other phenomena ranging from various forms of radiation to impact force determination, and from dependence on electrical properties to centrifugal force. The conditions and properties of the flowing solids have a major impact on the type of flowmeter required. For example, the flow rate of coal can be measured by microwave detectors or belt feeders. This choice is a function of the coal being pulverized and whether it is pneumatically conveyed.

Before undertaking a discussion of solids flowmeters, we will discuss associated process equipment such as solids storage devices and the feeders that bring the solids from the storage vessel. Because keeping solids in motion and preventing arching and rat-holing in the supply bins are serious problems, the description of feeders will be preceded by the topic of feeder accessories.

SOLIDS HANDLING EQUIPMENT

The bin, the feeder, and the solids flowmeter should be designed in an integrated manner, taking into account the characteristics (density, particle size, moisture content, temperature, or hazardous properties) of the solids. For example, the bed depth on a belt must be less than the height of the skirts (to avoid spillage), but it must be at least three times the maximum lump size to guarantee stable solids flow. Coarse materials (+60 mesh) or wet ores are likely to bridge or rat-hole in the bin (Figure 2.23a) and require vibrators and special feeders.

Similarly, aerated, dry, and fine solids (–200 mesh) are likely to either free-flow or be compacted and thereby plug the standard rotary vane or screw feeders. Changing the pitch or inserting additional flights can alleviate flushing. Vibrators usually also help, although in some cases they might worsen the situation by packing the solids. In general, the addition of high-amplitude and low-frequency vibrators or air pads and the use of mass flow bins (steep walls at 10 to 30° from the vertical) tend to improve material flow.

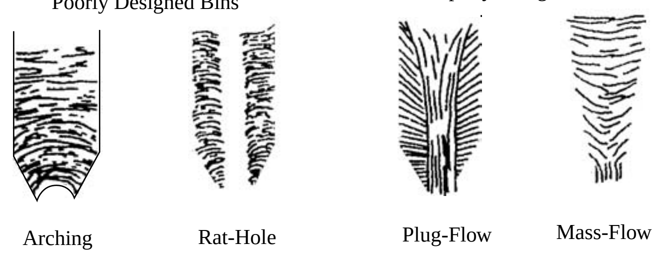


FIG. 2.23a
Good bin design is a critical requirement for a successful solids metering installation.

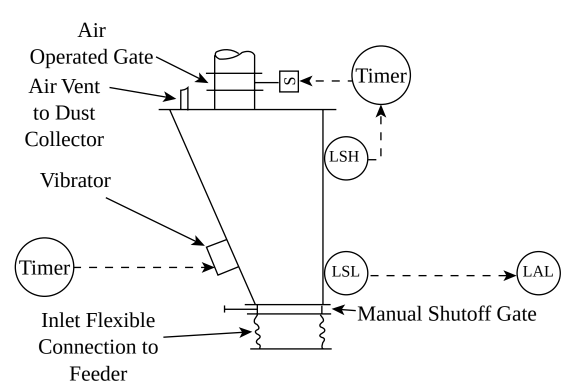


FIG. 2.23b
Deaerating surge hopper.

Hoppers and Accessories

A surge hopper, when located between the storage hopper and feeder inlet, provides a means of deaerating the solids. This guarantees that the solids can be fed, using a gate-controlled belt feeder, without causing flooding. The solid feed into the surge hopper is controlled by bin level switches (LSL and LSH in Figure 2.23b), which maintain the solids level within an acceptable zone by on–off control of the hopper supply gate valve. The hopper inlet device may be a rotary vane feeder, screw conveyor, or a knife gate with suitable actuator.

If the required feed rate is constant or nearly so, the bin switches are located so as to provide a hopper capacity that is equivalent to about 2 min retention time when operating at the design feed rate. In cases in which the material may compact in the hopper and interrupt the supply to the feeders, excess retention time is undesirable. If the feed rate is varied, an adjustable timer is incorporated in the level control circuit to adjust the time setting for keeping the hopper feed valve closed. This timer is started by the upper bin level switch (LSH), which simultaneously closes the bin supply valve when the material contacts the probe. This condition is maintained until the timer runs out and reopens the supply valve, which than stays open until the high-level detector is once again reached.

In this arrangement, the low-level switch (LSL in Figure 2.23b) serves only as a low-level alarm, which is used to shut down the feeder. Such shutdown is usually desirable to prevent loss of the plug of material ahead of the belt feeder. If the solids easily aerate, the loss of a plug of deaerated material can cause production delays, because a new supply of deaerated material has to be obtained first. Some materials will deaerate in the surge hopper without the need for vibration. Other materials require that the hoppers be furnished with electric or pneumatic vibrators. The required frequency and duration of vibration varies with solids characteristics and the vibrators therefore are provided with the means for adjusting these variables.

All manufacturers recommend that a feeder or meter be isolated from sources of vibration, and some include shock mounts with each machine. Inlet and discharge flexible connections to isolate the equipment from vibration and pipe strain in the material inlet and outlet ducting are also recommended.

Material Characteristics A number of common materials, of which sulfur is an example, will compact unless kept in almost continuous motion. Others will compact even while in motion if placed under the pressure of a relatively low head of material. In these applications, it is necessary to use small surge hoppers and use level switches that keep the head of material on the feeder belt low. The retention time of these small hoppers is on the order of a few seconds, and external vibration is not used.

The discharge flow pattern of a belt feeder varies with belt speed and material characteristics. A granular free-flowing material such as sugar will flow smoothly off the belt even at low belt speeds. Other materials having a high angle of repose coupled with a tendency to compact will drop off the end of the belt in lumps, especially at low belt speeds. This results in erratic feed rates and in short-term blend errors when part of multifeeder systems. The discharge flow pattern can be markedly improved by equipping the feeder with a material distributor. This device consists of a blade located across the full width of the belt at the discharge end of the feeder and vibrated by an electric or pneumatic vibrator. The blade is located so that it almost touches the belt and the material is directed across it. This vibration causes the solids to be spread out into a ribbon and to smoothly stream off the belt.

Unlike liquids, which exhibit predictable flow behavior, solids flow characteristics are extremely difficult to evaluate on any basis other than an actual trial. For this reason, most manufacturers maintain a test and demonstration facility in which samples of a potential customer's solids samples can be fed by various test feeders equipped with various volumetric feed sections. Recognizing that a wealth of experience with commonly used materials can very often permit a feed section recommendation without the need for testing, it also should be noted that even a minor change in the properties of a material can drastically change its feeding characteristics. These changes might be in particle size or particle shape but can also be caused by the entrainment of air, which occurred during pneumatic conveying prior to the solids entry into the feeder, or by the addition of an additive to the preblended solids.

Many installations involve feeding directly into processes that may be under low pressure or that may discharge corrosive vapors back through the feeder discharge ducting. If pressures are very low, the feeder can be purged with inert gas, or a rotary valve can be installed in the ducting. The rotary valve body should be vented to remove process vapors from the valve pockets before they reach the inlet or feeder discharge side of the valve. If the valve is not vented, blowback resulting from the release of pressure in the rotor pockets can cause discharge flow pattern disturbances and, in extreme cases, affect the feeder weigh section. The valve is vented into a dust or vapor collecting system via a vent port in the side of the valve rotor housing.

Taking Samples Feeder manufacturers base their performance guarantees on taking a timed sample, weighing it, and comparing the result with the setpoint of the feeder. This requires some means of sampling, which are available either as sample trays, which are inserted into the feeder discharge stream for a predetermined period and then weighed, or as flap valves, which temporarily divert the discharge stream from the process duct into a sampling container. The flap-type valve is generally preferred, because the tray-type sampler is suitable only for low feed rates. Sampling normally involves the taking of 10 consecutive 1-min samples and comparing the average sample weight to the setpoint. Another advantage of the flap-type sampler is that it is faster acting, and the sample weights obtained are thus more accurate.

Each feeder or meter is usually supplied with a test weight or drag chain, which may be used to check the calibration of the device without actually running material. The weight is usually selected to match the full scale of the weight-sensing mechanism. Such test weight is also useful in aligning the control setpoints in multifeeder master–slave systems prior to running any material. In such systems, the test weight can be applied to the master feeder, and the resultant output signal can be sent to the ratio station setpoints of the slave feeders.

Feeder Designs

A gravimetric feeder consists of a weight-rate measuring mechanism coupled with a volumetric feed rate control device. The vertical gate volumetric regulator, which is perhaps the most popular, is not suitable if the solids have large particle size, are fibrous, are irregularly shaped, or tend to flow like a fluid because of fine particle size. Because of this wide variation of solids properties, a variety of feeders have been designed as described in the following paragraphs.

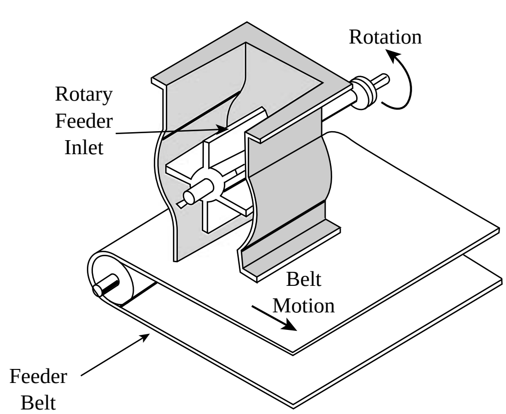
Vertical-Gate The vertical-gate gravimetric feeder is available in a variety of sizes to produce typical material ribbon widths of 2 to 18 in. (50 to 457 mm) and to regulate up to 6 in. (152 mm) of material depth on the weigh belt. Gate actuators may be electromechanical or pneumatic, or they may use computer-controlled electric servomotors or stepping motors. Manually adjustable gates are also available. The vertical gate has a typical depth control range of 10:1 and is generally suitable for materials that are not fluidized and that have a particle size not larger than about 0.125 in. (3.175 mm). Larger particles will not flow smoothly under the lip of the gate, thus resulting in an irregular belt load. This may require excessive damping of the belt load transmitter output, which will have an undesirable effect on both control accuracy and sensitivity. In addition to producing undesirable control characteristics, rangeability will be decreased as particle size increases. As a rule of thumb, the minimum gate opening should be approximately three times the maximum particle size for solids having irregularly shaped particles of random size. This 3:1 ratio may be reduced somewhat if the material is homogeneous and particles do not tend to interlock and tumble while in motion (typically, if particle shape approaches that of a sphere).

Rotary-Vane Figure 2.23c shows a rotary-vane feeder, which can be provided with a variable-speed drive and conventional or computer controls. Such a feeder is used as the volumetric feed section in instances in which the material is aerated or has a low bulk density. Rotary feeders are not recommended for handling solids with large particle sizes or if the solids are sensitive to abrasion by the feeding device. In solids-blending applications, it is possible to operate several feeders in parallel or in cascade from the same setpoint.

Similarly to the vertical gate feeder, the rotary-vane feeder is not suitable either for handling fibrous or stringy materials, because sticky or hygroscopic materials tend to clog the pockets of the rotor. The sizing of pocket shape and depth is based on the required volumetric flow rates and material characteristics. Volumetric capacity is regulated by rotor speed, but if the speed is too high, rotor pockets won't completely fill as they pass under the inlet opening, and volumetric output may decrease if rotor speed exceeds the optimum. Therefore, care must be taken in determining a maximum practical rotor speed.

The rotary-vane feeders therefore have limitations when used on applications involving free-flowing powders or materials having small particle size but, unlike the vertical gate, they can handle low-density or aerated materials. The rotary feeder should be separately mounted from the gravimetric meter and should be interconnected by means of a flexible connection to prevent transmittal of vibration from the rotary feeder to the weight-sensing meachanism. Figure 2.23c also shows a manually positioned leveling gate, which is located ahead of the weighing section. This device levels the irregular feed pattern created by a rotary feeder and produces a more consistent feed to both the weighing section and eventually to the process. The shutoff gate at the feeder inlet serves the isolation of the feeder from the material supply during inspections or servicing.

Screw Feeders The feeder element in this device is a screw whose rotary motion delivers a fixed volume of material per revolution (Figure 2.23d). The screw is located at the bottom of a hopper so that its inlet is always flooded with solids. Screws grooved in one direction discharge material at one end only. Screws grooved in opposite directions from the middle deliver material at both ends. Rotation of the screw



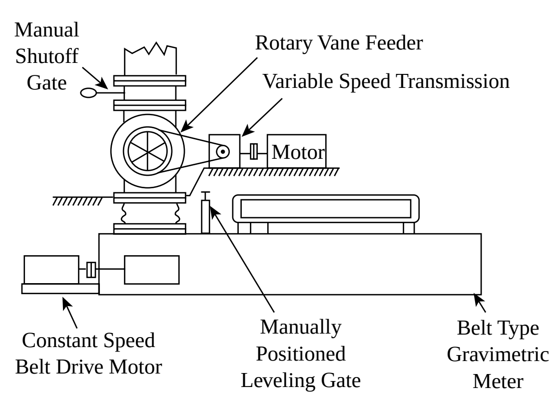


FIG. 2.23c
Gravimetric feeding system utilizing a rotary vane volumetric feeder controlled by a belt-type gravimetric meter.

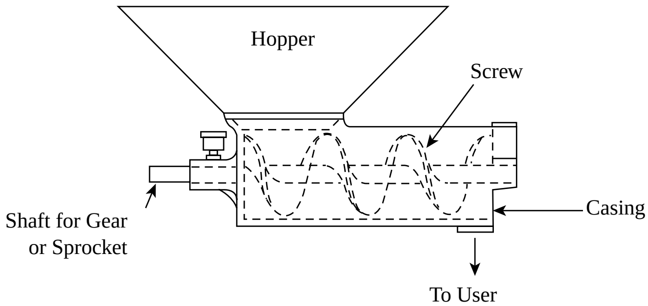


FIG. 2.23d
Screw feeder.

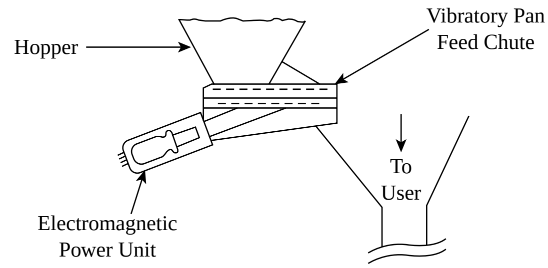


FIG. 2.23e
Vibratory feeder.

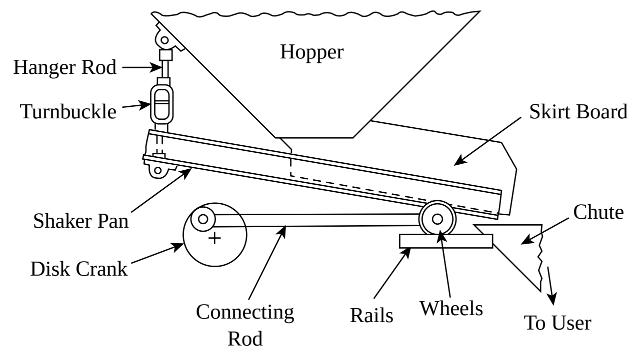


FIG. 2.23f
Shaker feeder.

can discharge material into receiving vessel(s), at one or both ends of the screw.

A variable-speed screw feeder can feed control low-density or aerated materials. The screw section can be made as long as is necessary to prevent the material from flooding through it. Screw feeders have also been successfully used on fibrous solids and on powdered materials, which tend to cake. The major advantage of the screw feeder, compared to a rotary vane feeder, is that custom-built screw feeders can be provided with extremely large inlet openings to facilitate the entry of fibers and coarse lumps into the conveying screw.

When the solids have a tendency to cake or clog the screw, the double-ended version of the screw feeder can be oscillated laterally. This oscillation imparts lateral forces that assist in moving the solids through the unit by alternately moving the material first toward one end and then the other.

To assure an accurate feed, the hopper on the inlet side of the feeder must be designed to provide a uniform supply of material to the feed screw. Vibrators can be added to the hopper to keep the solids agitated and to prevent caking and bridging.

Feeder drives are usually electric motors. If the drive is a constant-speed unit, the feed rate is adjustable over a 20:1 range by means of a mechanical clutch that varies the on–off operating time per cycle. In this case, if the feed rate is set at 75%, the screw feeder will be operating 75% of the time or 75% of a clutch revolution. The addition of an analog or digitally controlled variable-speed drive can extend the rangeability of the unit to 200:1.

Vibratory Feeders Vibratory feeders are used in gravimetric feeding systems to handle solids with particles that are too large to be handled by screw, rotary-vane, or vertical-gate feeders, or in operations where the physical characteristics of the solid particles would be adversely affected by passage through these volumetric feeding devices. The discharge flow pattern of a vibrating feeder is extremely smooth and thus is ideal for continuous weighing in solids flow metering applications.

The vibratory feeder (Figure 2.23e) consists of a feed chute (which may be an open pan or closed tube) that is moved back and forth by the oscillating armature of an electromagnetic driver. The flow rate of the solids can be controlled by adjusting the current input into the electromagnetic driver of the feeder. This input controls the pull of the electromagnet and the length of its stroke. Vibratory feeders are well suited for remote computer control in integrated material-handling systems.

The vibratory feed chute can be jacketed for heating or cooling, and the tubular chutes can be made dust tight by flexible connections at both ends. The vibratory feeders can resist flooding (liquid-like flow) and are available for capacity ranges from ounces to tons per hour.

Shaker Feeders The shaker feeder (Figure 2.23f) consists of a shaker pan beneath a hopper. The back end of the shaker pan is supported by hanger rods. The front end is carried on wheels and is moved by a crank. As the pan oscillates, the material is moved forward and dropped into the feed chute.

In most units, the number shaking strokes is kept constant while the length of the stroke is varied. The angle of inclination of the shaker varies from about 8° for freely flowing solids to about 20° for sticky materials. If arching is expected in the hopper, special agitator plates are installed in the hopper to break up the arches. The shaker feeder is rugged and self-cleaning, and it can handle most types of solids regardless of particle size or condition.

Roll Feeder Roll feeders are low-capacity devices used for handling dry granules and powders (Figure 2.23g). The feeder consists of a feed hopper, two feed rolls, and a drive unit. Guide vanes in the hopper distribute the material and provide agitation by oscillation. The feed rolls form the material into

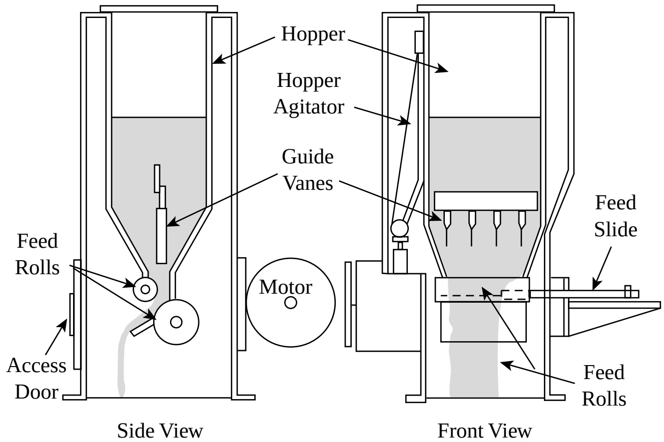


FIG. 2.23g
Roll feeder.

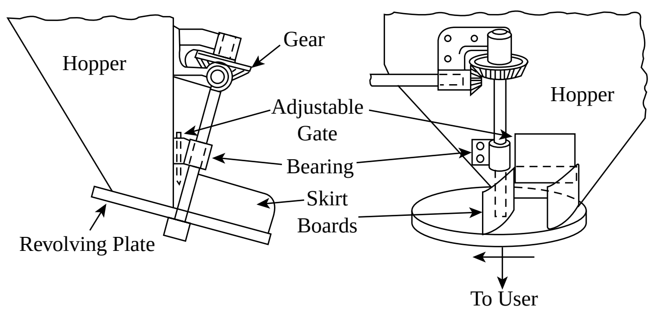


FIG. 2.23h
Revolving plate feeder.

a uniform ribbon, and the feed rate is controlled either by means of a slide that varies the width of the ribbon or by means of a variable-speed drive. The rangeability is typically 6:1 when using the feed slide and 10:1 when variable-speed drives are used. For materials that tend to cake or bridge in the hopper, agitators can be provided to maintain the material in a free-flowing state.

Revolving-Plate Feeders Revolving-plate feeders (Figure 2.23h) consist of a rotating disk or table (usually horizontal), which is located beneath the hopper outlet. The table is rotated and, as it rotates, fresh material is drawn from the hopper while the solids that the feeder discharges are scraped off by skirt boards. The feed rate is controlled by adjusting the height of the gate or positioning the skirt board.

Revolving-plate feeders handle both coarse and fine materials. Sticky materials are also handled satisfactorily, because the skirt boards are able to push them into the chute. This type of unit cannot handle materials that tend to flood. A variation of the revolving plate feeder utilizes rotating fingers to draw feed material from the bin. Revolving-plate feeders can also be equipped with arch-breaker agitators in the conical throat section of the hopper.

GRAVIMETRIC FEEDERS

Belt feeders are compact factory-assembled devices that use belts to transport the material across a weight-sensing mechanism. In the case of solids flowmeters, the flow of solids is uncontrolled, and the load on the constant speed belt is measured as an indication of the solids flow rate. The flow rate of solids on a simple gravimetric feeder can be regulated by a vertical or rotary gate, screw, or other volumetric control device. More accurate control methods are based on varying the belt speed or adjusting both the belt speed and the belt loading. (Although this volume of the *Instrument Engineers' Handbook* is devoted only to measurement, in connection with gravimetric belt feeders, it is also necessary to touch upon the topics of regulation and control, which will be discussed in much more detail in the second volume.)

Early Belt Feeder Designs

Figure 2.23i illustrates the forerunner of most modern belt feeders. It consists of a constant-speed belt coupled to a gate that modulates the solids flow rate so that the belt load is balanced by an adjustable poise weight. This feeder is unique in its simplicity but is inferior to the more modern designs for the following reasons:

1. The entire feeder is weighed rather than only a portion of the belt. Consequently, the ratio of live load to tare weight is low. In addition, the mechanical friction in the pivots results in a low sensitivity in the belt load-detection system.
2. This is a proportional-only controller, because the opening of the gate control element is proportional to the belt load error. Much as a float-operated level-control valve cannot maintain the level at setpoint if valve supply pressure or tank draw-off vary, this feeder cannot maintain the solids flow rate if the bulk density of the solids changes.

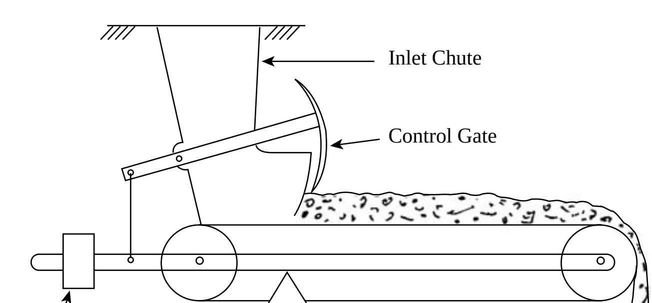


FIG. 2.23i
Early belt-type mechanical gravimetric feeder.

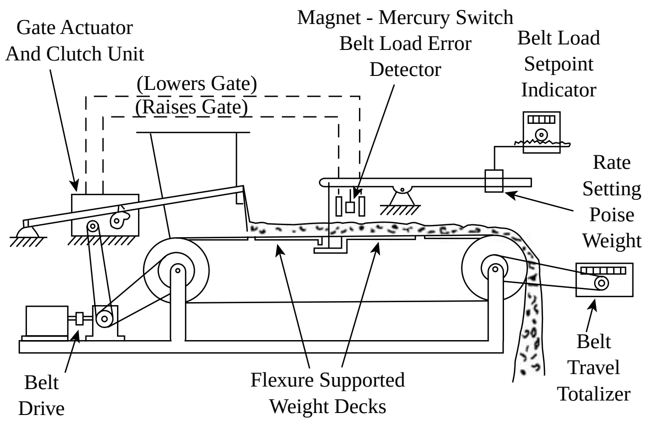


FIG. 2.23j
Belt-type electromechanical gravimetric feeder.

Figure 2.23j illustrates another early electromechanical gravimetric feeder design. Here, the belt load is balanced by a poise weight on a mechanical beam, which also carries a magnet. If the beam is not balanced, the magnet energizes one or the other of two clutches via a pair of mercury switches, which are energized by the magnet. These clutches actuate and establish the direction of travel of the gate-positioning mechanism. The gate modulates the belt loading to keep it constant and matched with the belt load set by the poise weight on the balance beam.

This feeder will maintain the belt loading regardless of changes in material density and subject only to the volumetric control limits of the gate. In this design, the belt load setpoint can be indicated by a mechanical counter that is geared to the beam poise weight drive. A second counter can be geared to the belt drive, which can give the total length of belt travel. The total weight of solids fed can thus be calculated by multiplying the readings of the two counters.

In more up-to-date versions of this design, remote setpoint and the measurement signals are provided, along with automatic shutdown, after the desired total weight of material has been fed. Gate position-actuated adjustable limit switches can be provided to activate alarms that can indicate either the stoppage of the supply of solids to the feeder or the overtravel of the control gate resulting from abnormally low material density.

Feed Rate Control

The feed rate of all belt-type gravimetric feeders is a function of the belt speed and the unit loading of the belt. If belt speed is expressed in feet per minute and belt loading in pounds of solids per foot of belt, the solids flow is obtained as

$$\text{Flow rate} = (\text{Belt speed})\,(\text{Belt loading}) = 1\text{bm/min} \qquad \mathbf{2.23(1)}$$

In the case of the constant-speed belt feeders previously discussed, the flow rate of solids is directly proportional to

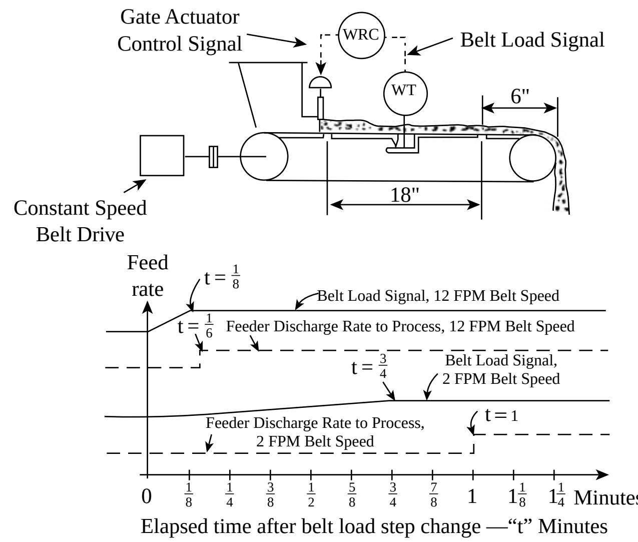


FIG. 2.23k
Open loop response to a step change in belt loading.

belt loading. Another method of flow rate adjustment is to vary the belt speed while maintaining the belt loading constant. The third option is to vary both the belt speed and the belt loading, in which case the flow rate is obtained as in Equation 2.23(1).

Belt Load Control of Constant-Speed Belts A standard constant-speed belt feeder, provided with a pneumatic gate actuator, is shown in Figure 2.23k. The length of the weighing section and the distance from the end of weighing section to the end of belt are approximately the same as those in an actual feeder. The response shown in Figure 2.23k is not precisely depicted, because it assumes instantaneous gate response and does not consider the controller lags, but these effects are minor in comparison to the effect of the belt transportation lag, which is the major source of concern in using constant-speed belt feeders.

The uppermost curve shows the response of the belt load signal to a step change in belt loading if the belt is moving at a speed of 12 ft/min. The dashed line below represents the instantaneous feeder discharge rate at the end of the feeder belt. This is the solids flow rate that the process downstream of the feeder receives. By reviewing the top line, one can conclude that some effect of the stem change in belt loading is sensed almost immediately after the step change, because the control gate is located at the upstream edge of the weighing section. At the 12-ft/min belt speed, the full length of the weighing section will be covered by the new level of solids in 18/144 = 1/8 min after the step change. Yet, at that time, the feeder is still discharging at the rate, that existed prior to the step change, and an additional 1/24 min is required to transport the material to the end of the belt—a distance of 6 in.

If the belt speed is 2 ft/min, the corresponding feeder response will be as described by the lower pair of curves in

Figure 2.23k. In this case, it will take a full minute before the downstream process starts receiving the new solids flow rate after a step change in belt loading is made. Such response times might be tolerable by some single-feeder processes, but not all.

Belt Speeds and Blending In continuous blending operations, the instantaneous blend ratio must be continuously maintained, so acceptability of constant-speed feeders is more limited. We can conclude from the data in Figure 2.23k that, if two feeders having belt speeds of 12 ft/min and 2 ft/min were controlled from a common belt loading signal, and a step change occurred in that signal, the result would be a temporary upset in the actual blend ratio. This upset would start 10 sec after the change in the belt loading setpoint and would persist for a period of 50 sec, at which time the original blend ratio would be restored.

Therefore, blend ratios that are obtained from two or more constant-speed gate feeders cannot be maintained unless the belt speeds of all feeders are identical. This is a serious limitation, because, in blending application, it is rarely possible to size a number of feeders that are delivering different solids flow rates so that they all have the same belt speed. If the solids flow characteristics permit it, one can increase the belt speed by decreasing the width of the material ribbon on the belt, but this does not satisfactorily solve the problem in most applications.

The blend ratio upsets can be reduced if the feeders are cascaded in a master–slave relationship wherein the step change in the belt load is first applied to the master feeder's gate actuator, and its belt load signal is used to control the gate actuator of the slave feeder. One should always select the slow speed feeder as the master, because slaving the low-speed feeder to the high-speed one will only increase the duration of the upset in blend ratio. Computer studies indicate that the upsets in blend ratio will be minimized if the belt speed of the slave feeder is 1.5 times that of the master.

Belt Speed Selection Guidelines

1. In single-feeder applications, optimal response is obtained by selecting the maximum possible belt speed commensurate with the characteristics of the material being fed and with the belt load limits established by the feeder manufacturer.
2. In continuous blending applications involving two or more feeders of identical speed, the upsets in blend ratio caused by step changes in loading will be minimized if the feeders are controlled in parallel from a common loading-rate signal.
3. In continuous blending applications, where the constant-speed belt feeders have different speeds, the upset in blend ratio can be minimized by arranging the individual feeders in a cascaded (master–slave) configuration and selecting the lowest-speed feeder as the master. The upsets in blend ratio will be minimized if the speed of the slave is 1.5 times that of the master.

Varying the Belt Speed The main advantage of belt speed control over belt load control is that the solids flow to the process changes almost simultaneously with a change in belt speed setpoint. The use of speed control in multifeeder blending applications eliminates the blend ratio error that was caused by the differential transport lag, typical of constant-speed feeders. In variable speed blending systems, a common speed signal is applied in parallel to manipulate the speeds of all feeders, increasing or decreasing the total throughput of the blended solids.

The ratio of any ingredient in the total blended product can be modified by changing either the belt load or the belt speed of the corresponding feeder. The latter method is preferred if the ratio has to be changed while the system is operating, because the changing of belt loading during operation will cause a temporary blend error due to the transport lag between the control gate and the process. If a continuous integrator is used, it will accurately register the total solids flow, no matter if the blend ratio was manipulated by changes in belt loading or in belt speed.

Limitations of Belt Speed Control While the manipulation of the belt speed guarantees fast response to setpoint changes and eliminates the transport response error in blending, it also has some disadvantages.

1. One disadvantage relative to constant-speed feeders is that the variable-speed design does not provide feed rate readout. Therefore, the feed rate must be calculated by multiplying the belt speed times the belt loading.
2. In multifeeder blending systems every change in the blend ratio requires a change in the belt loading or in the speed ratio setpoint to one or more of the feeders. This, in turn, will change the total throughput to the process unless a master speed adjustment is made to compensate.

To overcome the above limitations, it is necessary to measure both the belt speed and the belt loading and, based on these two measurements, calculate the total solids flow rate, which then can be compared to a single setpoint representing the required feed rate. Figure 2.23l illustrates such a control configuration.

In the older, pneumatic version of this control system, the belt speed rangeability was 10:1. In the electronic version, where silicon-controlled rectifier (SCR) drives are utilized, the rangeability of speed variation is at least 20:1. In Figure 2.23l, the feeder is equipped with a fixed gate. This is acceptable in all applications where the material density is constant enough that the adjustment rangeability of the belt speed drive can accommodate all variations in both density and gravimetric feed rate. If the density variation is substantial, or if the feeder is to be used on a variety of materials having different bulk densities, the rangeability of belt speed adjustment might be insufficient. In such cases, a secondary or slave control loop is added to manipulate belt loading.

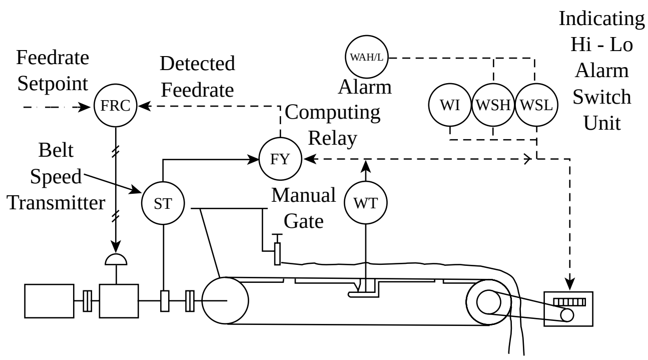


FIG. 2.23l
Speed-controlled belt feeder with both set-point and measurement in feed rate units.

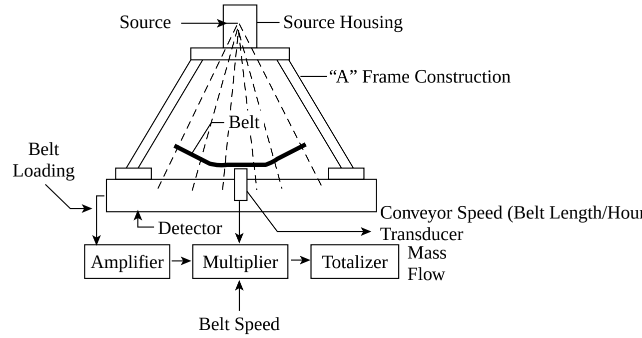


FIG. 2.23m
Nuclear belt scale supported by A-frame. (Courtesy of Kay-Ray-Sensall.)

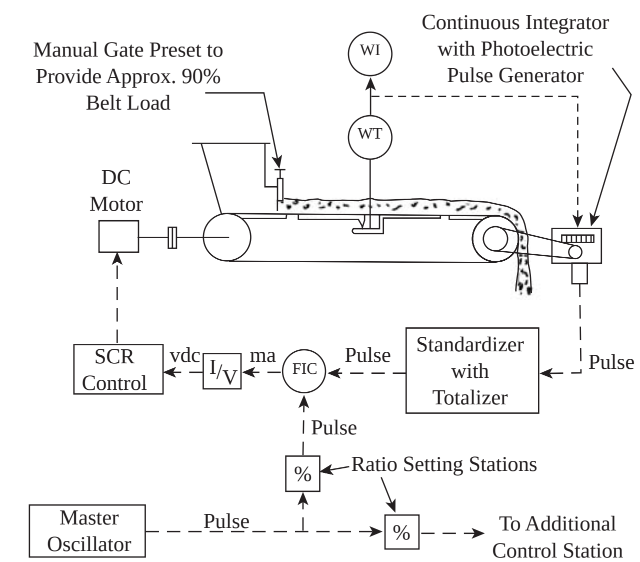


FIG. 2.23n
Belt-type gravimetric feeder with digital controls.

Precision of Weighing Weighing accuracy is the highest if the belt loading is maximized. This, in turn, will maximize the live load to dead load ratio. Gravimetric belt feeders are sized to handle the maximum required solids feed rate when the belt drive is operating at near maximum speed and the belt loading is at about 90% of maximum, based on the minimum expected material density.

To allow accurate setting of the manual gate position, a belt load indicator is desirable. To remind the operator that the manual gate opening needs to be readjusted because of changes in solids density, belt loading alarms are recommended. Such high and low alarm switches (LSH, LSL), as shown in Figure 2.23l, can simultaneously actuate audible alarms and initiate computer printouts.

Nuclear Belt Loading Detectors Belt loading can also be measured by detecting the radiation absorption of a discrete length of material. In all other respects, the nuclear belt scales are similar to gravimetric belt scales except that the load cells are replaced by nuclear densitometers. These devices have been used successfully not only on belt feeders but also on screw, drag chain, and vibrating feeders. The radiation source can be cesium 137, cobalt 60, or americium 241. The radiation source is usually placed above the belt and is supported on either side by a C- or A-frame (Figure 2.23m). In this configuration, the radiation detector is located below the belt and receives a radiation intensity that is inversely proportional to the mass of solids on the conveyor.

Nuclear belt scales are suited for such hard-to-handle services as hot, abrasive, dusty, and corrosive materials. If the moisture content, bulk density, and particle size of the solids are all constant, they can measure the belt loading within an error limit of 0.5% of full scale when the belt load is high (70 to 100% of full scale). On the other hand, if dissimilar solids are intermixed and measured by the same scale, the differences in radiation absorption characteristics can result in substantial errors. For nuclear belt scales, the minimum required belt loading is about 2.5 lb/ft^2 (12 kg/m^2), and these units are not recommended for belt runs that are shorter than 10 min or for belt loadings that are below 10% of full scale.

Digital Control The continuous integrator at the bottom right of Figure 2.23l totalizes the quantity of solids delivered by multiplying belt travel times belt loading. The instantaneous rate of integration is the rate of feeding the solids. Therefore, if the continuous integrator was provided with a feed rate transmitter, the belt speed transmitter (ST) and feed rate relay (FY) in Figure 2.23l could be eliminated, and the feed rate signal from the integrator could be sent directly to the feed rate controller (FRC). Figure 2.23n describes this arrangement, which has been developed for use in commercial digital control systems.

The digital control system is theoretically without error, because the pulses generated by the master oscillator in Figure 2.23n must be matched by those derived from the pulses generated by the integrator transmitter on the feeder. Laboratory evaluations and field tests have shown that the feeding precision based on weighed samples vs. total integrator pulses is better than 0.5% of feed rate over a 10:1 feed rate range.

Digitally controlled gravimetric feeders are utilized in situations involving a number of materials that must be blended in a wide variety of frequently changed formulations. High accuracy, high speed, ease of formula change, and centralized control characterize the digital control system. Although the cost of the feeder and its associated digital control is perhaps 50% higher than the cost of a feeder with conventional analog controls, digital control is widely used in continuous blending systems, particularly in the food industry.

Digital systems are superior to analog ones, because each pulse represents a specific increment of weight. Therefore, a pulse rate of 100 pulses per minute, for example, with a pulse value of 2 lb, signals a solids flow of 200 lb/min. The pulses are totalized on both the measurement and the setpoint side, so errors due to temporary starvation or overcharge, common in analog systems, cannot occur in digital ones. Another advantage of the digital system is the flexibility of the microprocessor, which can easily and quickly be reprogrammed, for example, for operating like a mass flowmeter or being part of a blending system.

The microprocessors also provide the capability for automatic recalibration and retention, for future reference, of the corrections that were applied at each test. The microprocessor-operated units are also capable of functioning in several modes, such as in start-up, predetermined fixed flow, or flow-ratio modes. They can have a variety of ratio or cascade configurations, logic interlocks, input and output signals (BCD, serial, analog), displays, printers, and memory units. They can receive their setpoints from other systems and also can receive stop/start signals as a function of other operations in the plant. They can operate as PID loops with dead time compensation utilizing such algorithms as "sample" and "hold," and, finally, they can operate as batching units with remote resets.

Batch vs. Continuous Charging Digital control systems are available in two basic arrangements: one for batching systems, the other for continuous feeding systems. In the batching version, the master oscillator in conjunction with a timer delivers a total number of pulses that are proportional to the desired total weight of solids. The pulse frequency is adjusted to vary the duration of the batch preparation period. The pulses are applied as the setpoint to the feed rate controllers (FIC in Figure 2.23n) via ratio setting stations for ingredient ratio. The feed rate measurement pulses are generated by the photoelectric pulse generator, which is driven by the feeder integrator. These pulses are sent to the feed rate controller after being scaled and standardized.

The controller compares the setpoint and measurement pulse frequencies and adjusts the feed rates as required by varying belt drive speed. In the batch controller version, a memory feature is also included so that the feeder continues running until it has generated the total number of pulses that equal the total pulses received as the setpoint by the feed rate controller from its ratio station. In a multifeeder batching system, this feature may result in feeders shutting down at different times, but the batch blend ratio will be correct.

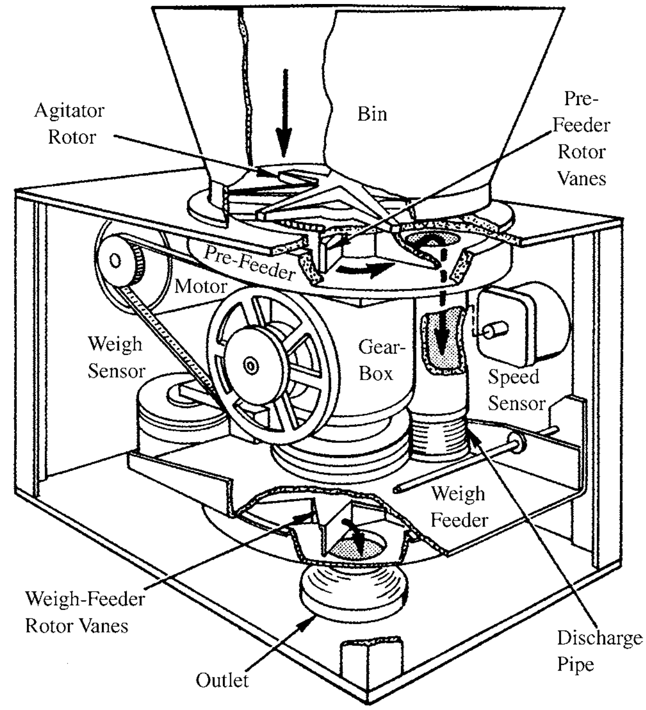


FIG. 2.23o
Vertical gravimetric feeder.

In continuous systems, another version of controller is used. It includes a pacing feature, which paces down all the feed rates if the feed rate of one feeder drops. Therefore, if the controller cannot correct a decrease in feed rate of one feeder, the corresponding controller will "gate" the output of the master oscillator and thus will pace down the feed rates of the other feeders to maintain blend ratio. When the faulty feeder corrects or is corrected, all feeders are automatically returned to normal control, and the master oscillator continues to set the feed rate. If the faulty condition persists for some predetermined period, an alarm is activated.

Vertical Gravimetric Feeders

A vertical gravimetric feeder is illustrated in Figure 2.23o. An agitator rotor within the supply bin guarantees a "live" bin bottom. The process material enters through a hole in the top cover of the pre-feeder and is swept through a 180° rotational travel by the rotor vanes until it is dropped into the discharge pipe. The solids are weighed along with the rotary weight feeder as it transports the solids to the outlet.

The advantages of this feeder include its convenient inlet–outlet configuration; its sealed, dust-tight design; and its self-contained nature wherein all associated control instruments are also furnished. After calibration, ±0.5% of full scale performance can be expected if a 5:1 rangeability is sufficient. At a 20:1 rangeability, the error, if the unit is calibrated, is ±1% of full scale.

The main disadvantages of this design are that the unit has a limited capacity and can only handle dry and free-flowing powders with particle diameters under 0.1 in. (2.5 mm). Large foreign objects cannot be tolerated in the process material, nor can damp or sticky solids that might cake or refuse to flow freely.

LOSS-IN-WEIGHT FLOWMETERS

One continuous loss-in-weight feeder design is illustrated in Figure 2.23p. In this system, the weight of the solids in the hopper is counterbalanced by a poise weight, which travels on the scale beam and is retracted at a constant rate. The controller modulates the speed of the rotary feeder so as to maintain the rate of retraction of the poise weight constant. The balance of the beam is maintained by increasing the rate of solids discharge if the weight of solids in the hopper exceeds that of the poise weight or decreasing the rate if it does not. Instead of a rotary feeder, the modulated control device can be a rotary screw feeder or a vibratory feeder.

The loss-in-weight systems are suitable for handling liquids and slurries as well as solids, because the weight-sensing section of the system is a tank or silo rather than a horizontal belt surface, which is open on all sides. Manufacturers of such units claim that if the delivery time period is short, their feeder gives better precision than other continuous feeders, because in their case the weight is measured ahead of the solids discharge device. Therefore, if an error in flow rate exists, it is corrected before the material leaves the feeder and enters the process.

Continuous Operation

In this configuration, the supply hopper or tank is suspended off one or more load cells. Tension cells are preferred to minimize the errors caused by nonsymmetrical loading. The controller detects the weight sensed by the load cell(s) and subtracts it from its setpoint, which is generated by a programmer. In other words, the programmer generates a signal corresponding to a fixed reduction rate of the total weight in the hopper, and this signal becomes the setpoint. The difference between the weight of material in the hopper and the programmed setpoint weight is continually sensed, and the flow rate of the material exiting from the hopper is regulated to keep them in balance.

The hopper must be periodically refilled, and this filling cycle must be initiated before the hopper is completely empty. Consequently, a “heel” always remains in the hopper and serves to minimize the shock on the load cells at the beginning of the filling cycle. The filling operation is controlled by a differential gap controller and a material supply valve, gate, or feeder (not shown in Figure 2.23p). When the weight of material in the hopper drops to the preset “heel” weight, the differential gap controller starts the filling cycle and at the same time either “locks” the discharge flow regulating device in its last position or closes it. When hopper weight reaches a high limit (corresponding to the filled condition), the differential gap controller stops the filling cycle and restarts the feeding cycle by returning control of the discharge regulator to the loss-in-weight control system. During the filling cycle, the feeding system is operating on a volumetric rather than on a gravimetric basis; hence, filling is accomplished as rapidly as possible. It is desirable to design these system such that the refill cycle is a small portion of the total cycle time.

Equipment

Hermetically sealed load cells are used that withstand not only dust and corrosion but are also compensated for temperature and barometric pressure changes. To withstand shock loading, the load cells should also be designed to withstand overloads of 150% of rating or more. If strain-gauge-type load cells are used, their power supplies should not only be closely regulated, but they should also be compensated for supply voltage variations. For loss-in-weight applications, tension-type cells are preferred, because the compression-type strain gauge load cells are sensitive to side load forces, which can be generated either by thermal expansion of the structure or by nonsymmetrical hopper loading.

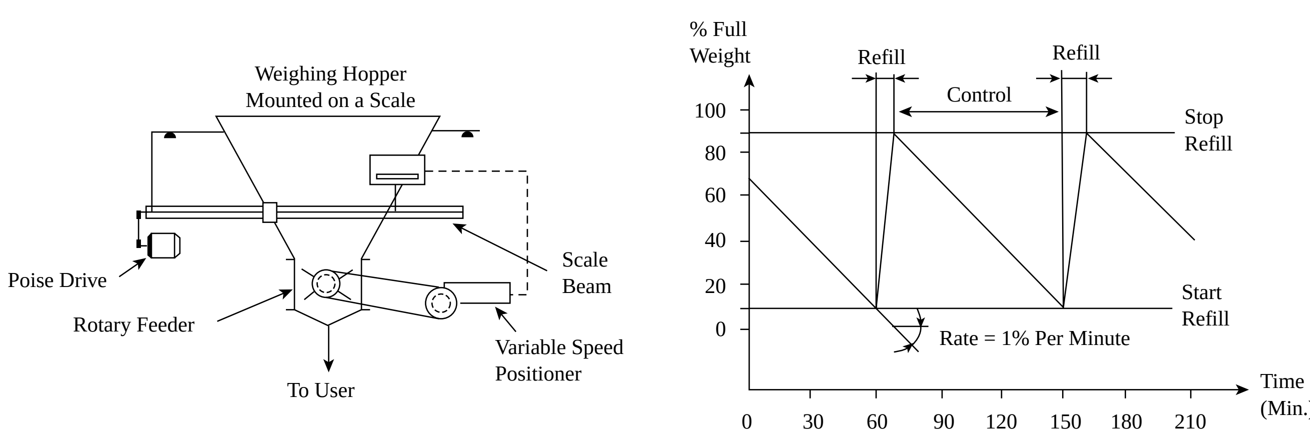


FIG. 2.23p
Continuous loss-in-weight feeder.

The weigh hoppers are often supplied by the user rather than by the supplier of the loss-in-weight feeding system. Their design criteria should not only include capacity and structural strength considerations but should also aim for minimum weight, because the tare weight should be minimized for maximum weighing sensitivity.

The material discharge regulator can be a control valve if the material is a liquid or slurry. Solids can be controlled by a rotary vane, belt, or vibrating feeders or by positioned knife gate valves. The choice is based on the required feed rate and on the physical characteristics of the process material.

System Sizing

In designing a loss-in-weight feeder system, the most important component is the hopper or tank. On the one hand, the hopper should be as large as possible, because the larger the hopper, the longer will be the running cycle and less frequent the filling cycle. On the other hand, for a particular feed rate (loss-in-weight rate), the system accuracy will decrease as the weight of the hopper and its contents increases. Therefore, a compromise is needed between these conflicting considerations.

It is recommended that the hopper be sized to hold the equivalent of about 15 min of discharge or approximately 15 times the maximum pounds-per-minute flow rate. The “heel” should equal 1/3 of the total hopper capacity, and the size of a charge during a refill cycle should be set to 2/3 of the total hopper capacity. The refill cycle should be completed in about 1 min or in less than 10% of the total cycle time.

CONCLUSION

The loss-in-weight feeders are not truly continuous weight rate control systems, because the gravimetric rate control is interrupted during the refill cycle. As a consequence, high accuracy totalization of the charge is not possible, although counters are available to indicate the number of times the hopper has been refilled.

The loss-in-weight systems are not used to feed easy-to-handle, free-flowing materials, because the belt-type gravimetric feeders are less expensive and suited for those applications. Loss-in-weight systems are usually considered for hard-to-handle liquid and slurry services. When no flowmeter or metering pump is available to detect or control the flow of a highly viscous, nonconductive, corrosive, or abrasive liquid, it is then that they are considered, and many highly satisfactory applications have been reported.

DUAL-CHAMBER GRAVIMETRIC FEEDER

The feeder illustrated in Figure 2.23q consists of two independently weighed hoppers. While the solids are being discharged from weigh hopper A, hopper B is being filled by the feed of fresh solids. When chamber B has filled up to its target weight (while the weight of hopper A is tared off), the feed is switched to hopper A, and hopper B is weighed prior to its contents being discharged into the process. Once chamber B has been weighed, its contents are discharged into the

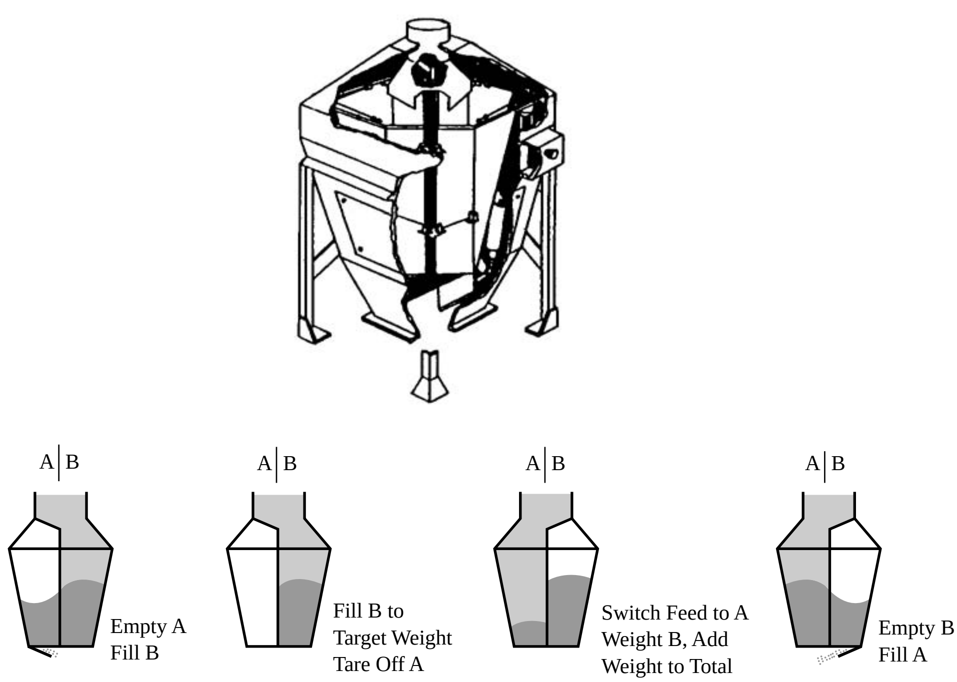


FIG. 2.23q
Dual-chamber gravimetric feeder. (Courtesy of Technicon Industrial Systems.)

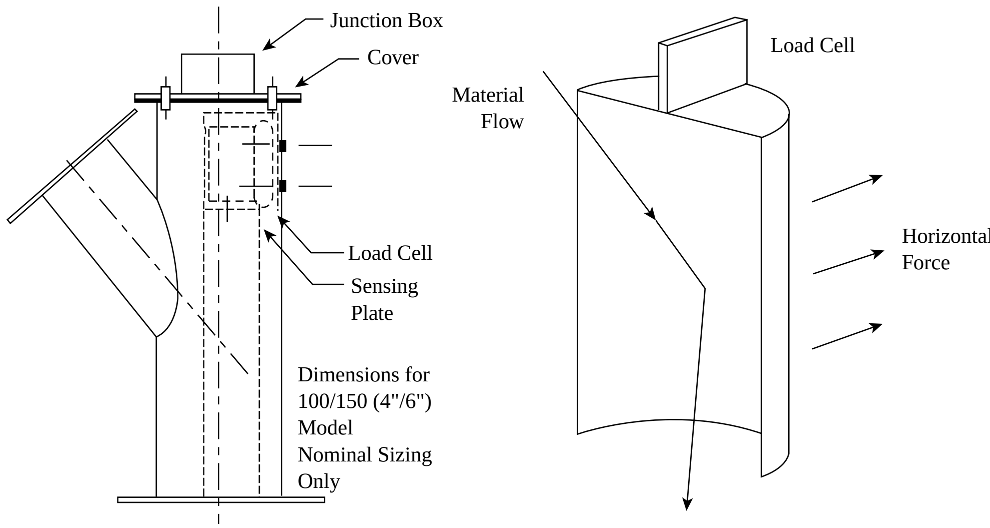


FIG. 2.23r
Cylindrical impulse flow element. (Courtesy of Milltronics Inc.)

process. After each discharge, the corresponding weight is added to the total weight that has previously been discharged.

The weighing cycle shown in Figure 2.23q is computer controlled. The only moving parts of the system are the diverter at the top and the two discharge gates at the bottom of the chambers. Because the hoppers are relatively small, their contents can be weighted accurately. The measurement error is usually about 0.5% of actual flow. Because the chambers are filled and emptied on a cycle period of around a minute, the discharged solids flow appears to be almost continuous. Where space is limited, the small size and vertical flow pattern of the equipment can also be of advantage.

This dual-chamber gravimetric feeder is suited for the measurement of free-flowing bulk solids and can be utilized as a continuous solids flowmeters or as batch recipe executors.

DYNAMIC SOLIDS FLOWMETERS

Whereas the previously discussed devices measure the flow rate while the solids are stationary on a belt or in a hopper, the devices described here measure the flow of falling or moving solid streams. These units detect either the forces needed to initiate the dynamic state by accelerating the solids or the forces resulting from the impact of the falling solids.

Impulse-Type Solids Flowmeter

When a stream of solids strikes a plate or a cylindrical surface at an angle, the resulting horizontal force component relates to its mass flow rate. The flowmeter illustrated in Figure 2.23r operates on the basis of this principle. The meter housing is manufactured from steel or stainless steel, and the sensing plate is made out of stainless steel. The units can handle free-flowing powers or granular and pelletized solid materials of up to 0.5 in. particle size.

The manufacturer claims both a very high sensitivity and wide rangeability (100:1). The smallest capacity unit is claimed to have a range of 300 to 30,000 lb/h (130 to 13,000 kg/h), and the largest unit can handle flows up to 650,000 lb/h (300,000 kg/h). The standard units can be operated at 140°F (60°C) temperature, but special units are available for operation at up to 450°F (232°C). Metering precision is claimed to be 1% of full scale. (If full scale is defined as the maximum flow the unit can handle, then at maximum turn-down, a unit with 100:1 rangeability will experience 100% error.) Microprocessor-based computer controls are available to integrate this flowmeter into batching or other automated material handling systems.

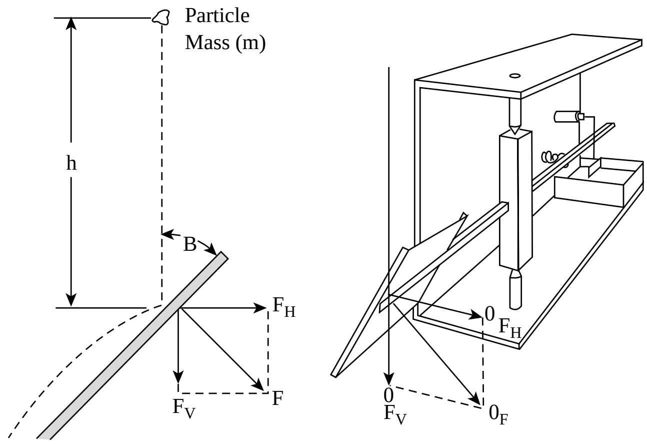
The principles of impulse and momentum detection have been used in liquid flowmeters such as the target, drag-body, and angular momentum designs. Their operation is based on Newton's second law of motion and on the conservation of momentum. These principles have also been successfully applied to solids flow measurement.

Figure 2.23s illustrates a design in which solid particles fall by gravity on a calibrated spring-loaded plate, the displacement of which is a function of the mass flow rate of the solids. A position transmitter is used to continuously detect the force caused by the falling particles.

Both of these solids flow transmitters (Figures 2.23r and 2.23s) can be used in continuous weighing applications. They can also be used in flow monitoring and control applications for batch or continuous services. Almost all types of solids can be measured by impulse-type flowmeters, including sugar, salts, cement, and ores.

Accelerator-Type Flowmeter

In this design, the solids stream enters the "accelerator" section of the meter by gravity (Figure 2.23t). The accelerator is driven at constant speed and, as the entering solids are



The horizontal component of the impact force on the plate is directly proportional to the flow rate of material over the plate

FIG. 2.23s
Impulse flowmeter. (Courtesy of Endress+Hauser Inc.)

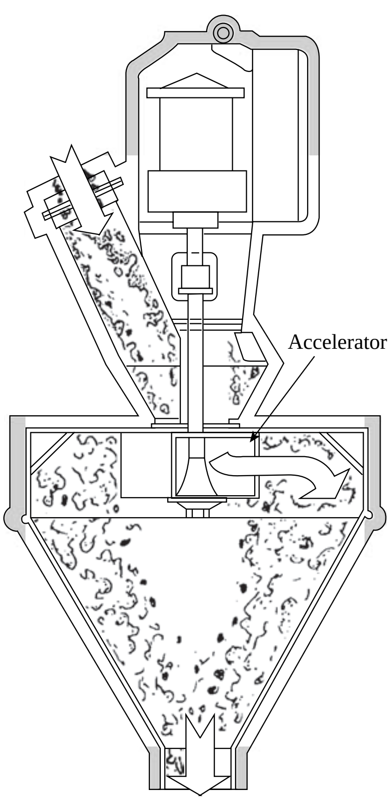


FIG. 2.23t
Accelerator-type solids flowmeter.

accelerated, they create a corresponding torque on the motor. Variations in this torque are detected by a torque transducer and amplified so that the transmission signal becomes directly proportional to the mass flow rate of solids.

The unit is designed for use on a wide range of materials, including powders, granules, pellets, and irregular solids as well as liquid slurries. The measurement rangeability of this

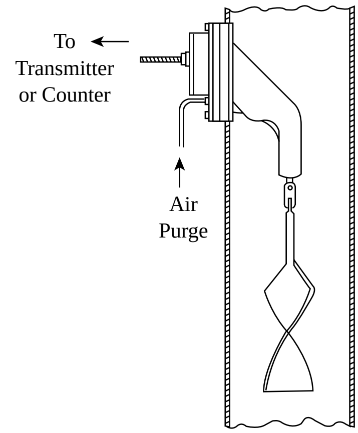


FIG. 2.23u
Volumetric solids flow detector.

flowmeter is fairly high (25:1), but so is the measurement error (around 2% FS).

Volumetric Flowmeters

The designs of volumetric solids flowmeters include the positive-displacement screw impellers, but if reasonable accuracy is desired, they should only be used to measure uniform-size solids such as lead shot. The operation of this type of instrument is similar to that of the turbine- or propeller-type liquid flowmeters except that a helical vane is used instead of the turbine.

As the flow of the falling granular material rotates the vane, a flexible cable transmits the rate of rotation to a counting mechanism mounted outside of the pipe or duct (see Figure 2.23u). This counting device can be a mechanical counter mounted directly onto the piping, or it can be a transmitter for remote monitoring and/or control. In this design, the transmitter output is determined by the position of a slotted cam. The cam is positioned by the balance between two rotations: the rotary motion produced by a synchronous motor and the rotary motion of the flexible cable.

The vane element is installed in the vertical position, and its bearing surfaces are protected by an air purge. To obtain acceptably accurate flow measurement, the instrument must be calibrated using the same process material, which it will measure after final installation. The measurement error of this flowmeter is around 3% of full scale, and its rangeability is about 10:1.

CROSS-CORRELATION SOLIDS FLOWMETERING

The concept of cross-correlation is based on tagging, which is the oldest of all flowmetering techniques. It consists of injecting some particles, a dye, a chemical, a radioactive material, or a pulse of any other form and measuring the time it takes for such a tag to travel a known distance. Cross-correlation flowmeters also detect the time of transit but, instead of tagging the process

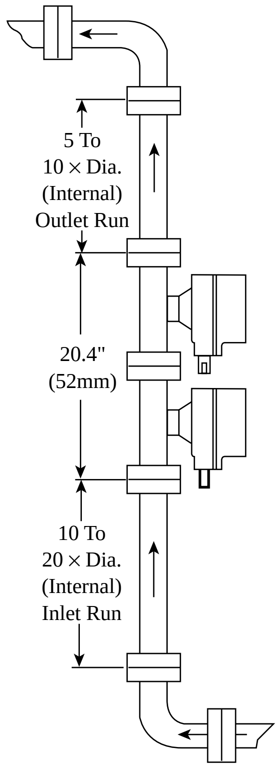


FIG. 2.23v
Solids flowmeter of the cross-correlation type. (Courtesy of Endress+Hauser Inc.)

fluid, they look at a noisy process variable and detect the time of travel of the recognizable noise pattern. If the noise pattern exists long enough to pass both detectors, computers are fast enough to recognize and interpret the readings.

The general subject of cross-correlation flowmetering is covered in more detail in Section 2.5. Here, we concentrate only on solids flow detection. A variety of sensors have been evaluated for this application, including gamma radiation, ultrasonic, and photometric designs. Figure 2.23v shows a solids flow detector that employs capacitance sensors. While further development is needed before reliable performance data can be reported, this metering technique does have potential, because it is not limited by hostile environments or by the characteristics of the solids being metered.

SOLIDS FLOW SWITCHES

Solids flow switches are used to detect abnormal flow conditions that result from either a flow or a no-flow condition. These can include detection of plugging or blockages, loss of feed, bridging in bins, overflowing of cyclones, rupture of bag filters, and the like. These switches should be both inexpensive and sensitive, because the amount of flow resulting from, for example, a bag rupture is not substantial. One solids flow switch (the *Triboflow*) that can detect such flows consists

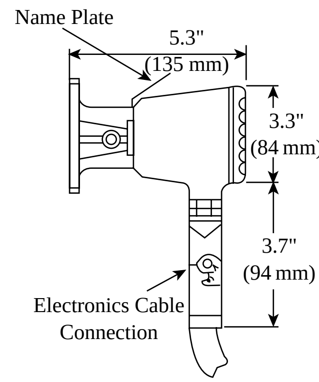


FIG. 2.23w
Microwave solids flow switch. (Courtesy of Endress+Hauser Inc.)

of a probe that collects the static charges of solid particles passing over its surface.

Microwave flowmeters of the continuous type are used to measure the flow of pulverized solids such as coal. Microwave switches detect the flow of solids by detecting only the motion or the absence of it. In a microwave motion detector, the transducer emits a 24-GHz signal into the flowing solid stream and analyzes the reflected frequency (Doppler effect) to determine the speed of the moving object that reflected it. The switch sensitivity is adjustable, so it may be used to trip at a velocity as low as 6 in./min (15 cm/min) when the pipe is full or at a velocity of one particle every 5 sec in a free-falling, gravity flow system. Units are available in aluminum or stainless steel. They can be connected to a pipe by a coupling or flange (Figure 2.23w) or can look through windows or nonmetallic walls without any openings. The units are intrinsically safe and can be used at working pressures up to 15 PSIG (1 bar). The switch can also observe motion at a distance of several feet from the detector and can tolerate the buildup of 0.5 in. of nonconductive coating or 0.1 in. of conductive coating.

MASS FLOW MEASUREMENT OF PULVERIZED COAL

To obtain the mass flow of pulverized coal being transported to a burner, one needs to know both the concentration (in mass density) and the velocity of the coal in the burner pipe. The main advantage of the technique described below is that it does not require *in situ* calibration, the use of isokinetic sampling, or rota-probing.

Detecting Mass Concentration

The concentration of the pulverized coal is measured using low-power, low-frequency microwaves, with each burner's pipe functioning as its own unique waveguide. Since the coal flow in all pipes served by the same mill has the same fuel source, variables such as moisture content, fineness, coal type, and so on are the same for all pipes. Therefore, the only

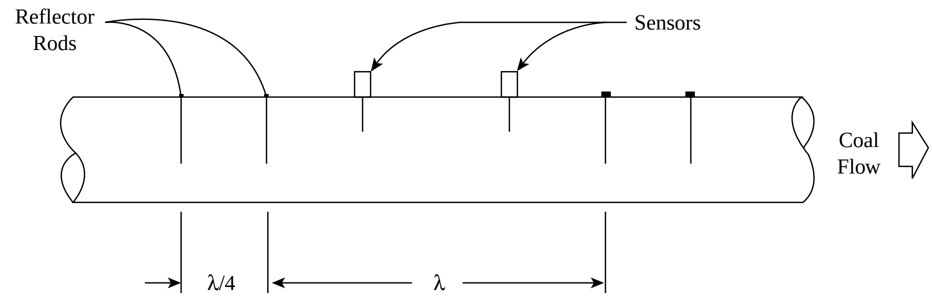


FIG. 2.23x
Standard Sensor and Rod Arrangement. (Courtesy of Air Monitor.)

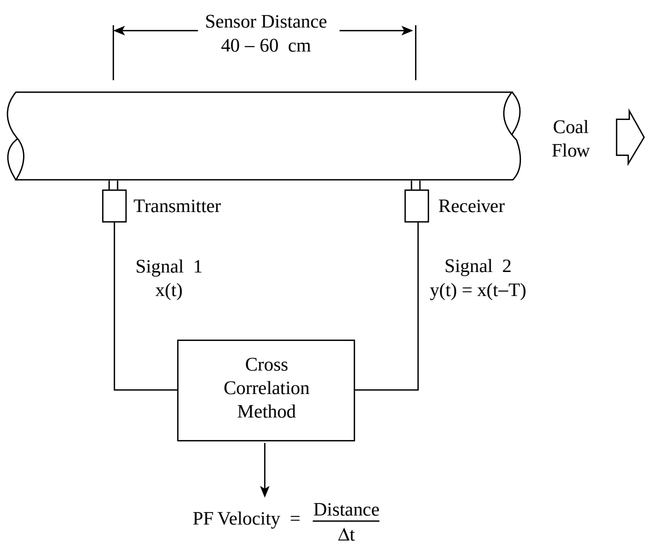


FIG. 2.23y
Cross-correlation configuration. (Courtesy of Air Monitor.)

pipe-to-pipe variable is the dielectric load, i.e., the concentration of the pulverized fuel in the section of pipe being measured. Starting with the measured microwave transmission characteristic of each empty pipe, variations in the dielectric load caused by changing coal concentration produce corresponding shifts in measurement frequency, resulting in quantifiable values that are reported as the absolute coal density in each pipe.

The concentration measurement is performed by two sensors aligned parallel with the longitudinal axis of the pipe; one functions as the microwave transmitter, and the other operates as the receiver, as shown in Figure 2.23x. Located upstream and downstream from the sensors are pairs of reflector rods—abrasion resistant, electrically conductive rods that prevent the microwave signal from leaving the measurement area and then being reflected back in the form of microwave noise.

Measuring the Coal Velocity

The velocity of the pulverized coal is measured by the cross-correlation method, which is conceptually depicted in Figure 2.23y. The same two sensors used for the measurement of coal concentration have a known separation distance. Stochastic signals created on the pair of sensors by the charged coal particles are nearly identical but are shifted by the time the pulverized coal needs to get from one sensor to the other. As the distance between the sensors is fixed, the velocity of the pulverized coal in the pipe can be accurately calculated.

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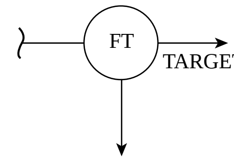
2.24 Target Meters

W. H. HOWE (1966, 1982) **B. G. LIPTÁK** (1995)
W. H. BOYES (2003)



Flow Sheet Symbol

Design Pressure	Up to 3000 PSIG (20.70 MPa) with strain-gauge type
Design Temperature	Up to 300°F (150°C) through 600°F (315°C) with strain-gauge type; special units up to 1200°F (649°C)
Sizes	0.5 to 8 in. (12.5 to 203 mm) with standard and up to 48 in. (1.2 m) pipes with the probe design
Fluids	Liquids, gases, and steam; also handles two-phase flows
Flow Range	From 1 GPM (3.785 l/min), 1 SCFM (28 l/min), 3 lb/h (1 kg/h) to practically any value using the probe design
Inaccuracy	±0.5% of full scale for standard and to ±5% of full scale for probe type
Materials of Construction	Usually carbon or stainless steel; PVC targets and internals available
Cost	\$1500 to \$10,000 as a function of size, design, and materials of construction
List of Suppliers	Aaliant Division of Venture Measurement (www.venturemeas.com) J.W. Sweet Co.

Material buildup in front of orifice plates can cause both measurement errors and plugging when the process stream is a liquid slurry or a gas carrying wet solids. The annular orifice and the target flowmeter were introduced to solve this problem by providing an annular opening for the solids to pass through. This design is no longer marketed, and the only type of target flowmeter sold today is the drag-body-type target meter.

The drag-body target flowmeter (Figure 2.24a) detects the impact forces produced by the flowing fluid by means of strain-gauge circuitry. This unit is available in standard configurations (Figure 2.24b) and is also available in retractable probe designs (Figure 2.24c), which are used in larger pipe sizes in which it is desirable to withdraw the sensor periodically for cleaning without opening the process line.

The target meter is applied in a number of fields for measurement of liquids, vapors, and gases. It allows unimpeded flow of condensates and extraneous material along the bottom of a pipe while allowing unimpeded flow of gas or vapor along the top of the pipe. It has given consistent, dependable service on “difficult” measurements such as hot, tarry, sediment-bearing fuels to a pipe still where no other head-type meter has proved successful. There are no differential-pressure connections to “freeze.” This is useful in steam flow measurement in exposed locations and for liquids that congeal at ambient temperature in pressure connections. Units are available for service up to 700°F (371°C), which is useful in steam service up to 200 PSIG (14 bars) pressure.

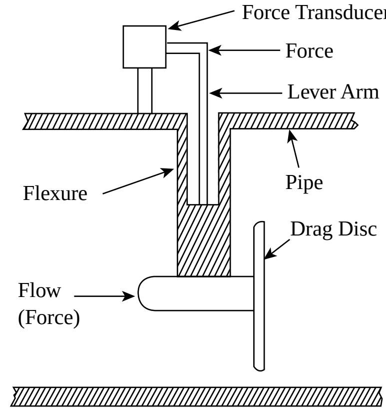


FIG. 2.24a
The drag-body flowmeter.

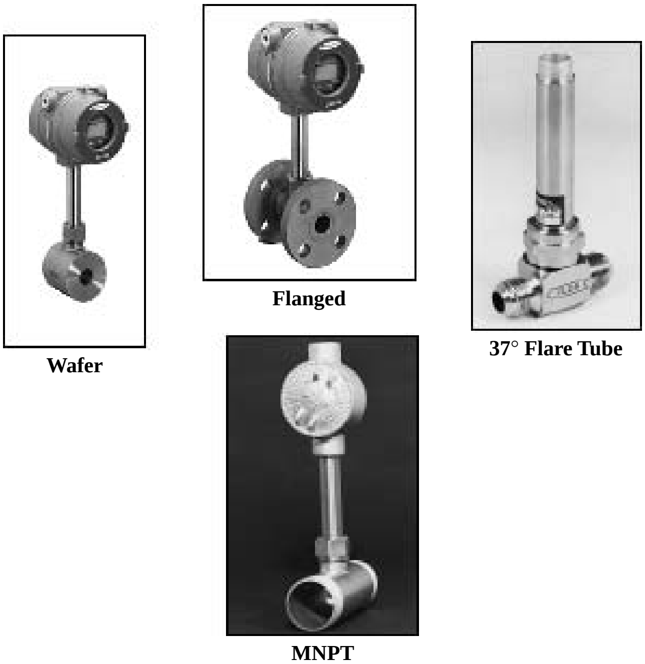


FIG. 2.24b
Standard target meter configurations.

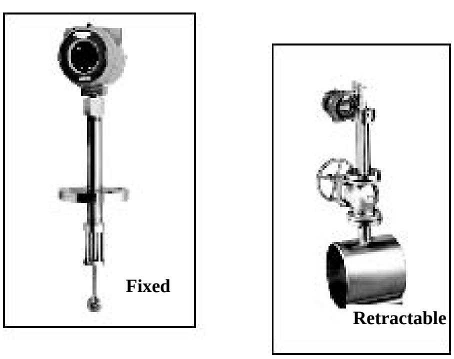


FIG. 2.24c
The insertion target flowmeter.

DRAG-BODY DESIGN

Drag-body targets are empirically derived, and a wide variety of sizes and shapes are available, according to the suppliers. Combined with wide-range force measurement transducers, a wide selection of full-scale flow rates is provided.

The manufacturers provide calibration data. The flow range through a particular-size meter can be varied by changing the target size and by replacing or readjusting the transducer.

Repeatability of output is good. Calibration accuracy includes not only the uncertainty of the primary element but also the characteristics of the transducer and the precision of the transducer adjustment. As is the case with some other proprietary devices, test data is unavailable for determination of flow coefficients from physical dimensions for different process fluids and operating conditions. On the other hand, target meters with accurate water flow calibration over almost any range of Reynolds numbers can be obtained. Transfer characteristics to other fluids based on Reynolds number are reliable. Because the transducer and the primary element are calibrated as a unit, overall accuracy of calibrated target meters is better than that of orifice-type systems.

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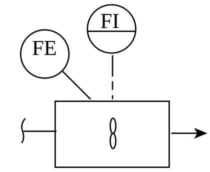
2.25 Turbine and Other Rotary Element Flowmeters

J. G. KOPP (1969) **D. J. LOMAS** (1982) **B. G. LIPTÁK** (1995)
J. B. ARANT (2003)



Flow Sheet Symbol

Types	A. Turbine flowmeters A-1. Single-Rotor A-2. Dual-Rotor B. Propeller, impeller, and shunt-flow types C. Insert, probe, or paddlewheel designs
Services	Relatively clean liquids, gases, and vapors (some units for gas service are also covered in Section 2.2)
Sizes	A-1. 3/16 to 24 in. (5 to 610 mm) in flow-through designs A-2. 0.25 to 12 in. (6.12 to 294 mm) in flow-through designs B. Impeller designs available from 3 to 72 in. (75 mm to 1.8 m) C. Paddlewheel units available for up to 12 in. (305 mm) pipes; insertion turbine probes not limited by pipe size, can also be used in open channels
Outputs	Generally, linear frequency outputs are provided, but 4- to 20-mA DC can also be obtained through conversion
Operating Pressure	A-1. 1500 PSIG (10.3 MPa) in standard and 5000 PSIG (34.5 MPa) in special designs A-2. ANSI 150 PSIG (1.03 MPa) up to ANSI 1500 PSIG (10.3 MPa) B. Impeller designs usually designed for 150 PSIG (1 MPa) C. Plastic paddlewheel units operable up to 200 PSIG (1.4 MPa) at ambient temperatures
Pressure Drops	A. Usually, one velocity head or about 3 to 5 PSIG (20 to 35 kPa) B. Usually less than 1 PSID (7 kPa) for the impeller types C. Negligible
Operating Temperature	A-1. –58 to 300°F (–50 to 150°C) in standard and –328 to 840°F (–200 to 450°C) in extended pickup designs A-2. –440 to 840°F (–268 to 450°C) B. Up to 160°F (71°C) for the impeller design C. The plastic paddlewheel units operable at up to 220°F (105°C) if operating pressure is <25 PSIG (<172 kPa)
Materials of Construction	A. Normally, stainless-steel housing and rotor with tungsten carbide sleeve bearings are used, but Hastelloy® C or other housing materials and ceramic or PTFE bearings are also available B. The impeller-type unit is provided with a plastic impeller and with aluminum, epoxy-coated carbon steel, or stainless-steel housing C. The plastic paddlewheel units are made of polypropylene, PVDF, Ryton™, and metallic parts
Error or Inaccuracy	A-1. Linearity is 0.25% of actual flow for turbine meters larger than 3/4 in. (19 mm) and 0.5% for smaller units. The repeatability (after calibration) is 0.02% of

actual flow. This performance assumes constant viscosity (within 0.3 and 3 cP) and density, proper installation including flow straighteners, a 10- to 15-diameter straight pipe run, and the use of a DC power supply and a preamplifier located at the meter.

A-2. 0.1 to 1% of actual flow with linearity and repeatability between 0.01 and 0.05%. Viscosity, density, velocity effects, and upstream straight run requirements are similar to A-1.

B. Shunt flowmeters are accurate within 2% of actual flow over a range of 10:1. The impeller-type units are also claimed to have a 2% of actual flow accuracy if operated at velocities exceeding 1 ft/sec (0.3 m/sec)

C. Linearity is 1% relative to actual velocity at point of insertion. Accuracy similar to pitot tubes, or 2 to 5%.

Rangeability

A-1. 10:1 unless limited by use of line-size units or by high process fluid viscosity
A-2. 10:1 to 500:1 for liquids and up to 1000:1 for gas flows
B. 10:1 for the shunt flow design
C. The optical designs provide flow rangeabilities in excess of 20:1

Cost

A-1. A turbine flowmeter with a preamp (but without readout electronics) and with 150-lb carbon steel flanges can be estimated as follows (1 in. = 25.4 mm): 0.5 to 1.5 in., $2200; 2 to 3 in., $2800; 4 in., $3500; 6 in., $5000; 8 in., $8000; 10 in., $12,000; 12 in., $16,000; 16 in., $28,000; 18 in., $32,000; 20 in., $50,000; 24 in., $75,000. Electronic readout devices might include auxiliary, explosion-proof power supply, $1200; remote register drive, $3500; frequency-to-analog converter with digital display, $1200; locally mounted, explosion-proof totalizer/flow indicator, $1200. Accessories include flow straighteners, strainers, batch control units, and two-stage shutoff valves.

A-2. Generally, 10 to 50% over A-1

C. The flow element of the plastic paddlewheel units for sizes between 0.5 and 12 in. (13 to 305 mm) costs between $250 and $500. Flow elements can be provided with analog indicators ($350), digital readouts ($500), recorders ($850), or batch totalizers ($600).

*Partial List of Suppliers**

ABB Instruments (www.abb.com/us/instrument) (A-1)
Badger Meter Inc. (www.badgermeter.com) (A-1)
Brooks Instrument (www.emersonprocess.com) (A-1)
Daniel Measurement and Control (www.danielind.com) (A-1)
Data Industrial Corp. (www.dataindustrial.com) (C)
Exact Flow (www.exactflow.com) (A-1, A-2)
Flow Research Corp. (www.flowresearch.com) (A-1)
Flow Technology Inc. (www.ftimeters.com) (A-1, C)
The Foxboro Co. (www.foxboro.com) (A-1)
Hays Cleveland (www.hayscleveland.com) (C)
Hoffer Flow Controls Inc. (www.hofferflow.com) (A-1)
Invensys Energy Metering (formerly Rockwell International, marketed by Equimeter) (www.invensysenergymetering.com) (A-1, A-2)
McCrometer (www.mccrometer.com) (B)
McMillan Co. (www.mcmillancompany.com) (A-1)
Miniflow Systems Inc. (A-1)
Omega Engineering Inc. (www.omega.com) (A-1)
Quantum Dynamics Inc. (A-2)
Rockwell Automation (www.automation.rockwell.com) (A-1)
Schlumberger Measurement Div. (www.slb.com/rms/measurement) (A-1)
Smith Systems Inc. (www.smith-systems-inc.com) (A-1)
Spirax Sarco Inc. (www.spiraxsarco.com) (A-1)
Sponsler Co. (www.sponsler.com) (A-1)

* *Note:* Most popular are units from Brooks, Daniel, Smith, Hoffer, and Badger.

Turbine meters are available for liquid, gas, and very low flow rates in both full-bore and insertion designs. The most widely used type is the full-bore meter for liquid service.

LIQUID TURBINE METERS

A turbine meter consists of a multibladed rotor suspended in the fluid stream on a free-running bearing (see Figure 2.25a). The axis of rotation of the rotor is perpendicular to the flow direction, and the rotor blades sweep out nearly to the full bore of the meter. The fluid impinging on the rotor blades causes the rotor to revolve. Within the linear flow range of the meter, the angular speed of rotation is directly proportional to the volumetric flow rate. The speed of rotation is monitored by an electromagnetic pickup coil, which is fitted to the outside of the meter housing. Two types of pickup coil are primarily used: reluctance and inductance. Both operate on the principle of a magnetic field moving through a coil.

In the reluctance pickup coil system, the permanent magnet is the coil. The field produced is concentrated to a small point by the cone (see Figure 2.25b). The turbine rotor blades are made of a paramagnetic material, i.e., a material that is attracted by a magnet. As a blade approaches the cone point, its magnetic properties deflect the magnetic field. This deflection causes a voltage to be generated in the coil. As the blade passes under the cone point, the voltage decays, only to be built back up in the opposite polarity as the departing blade deflects the magnetic field in the opposite direction. Thus, each blade produces a separate and distinct voltage pulse as it passes the cone. Because each blade sweeps a discrete volume of fluid, each electrical impulse represents the same discrete volume of fluid.

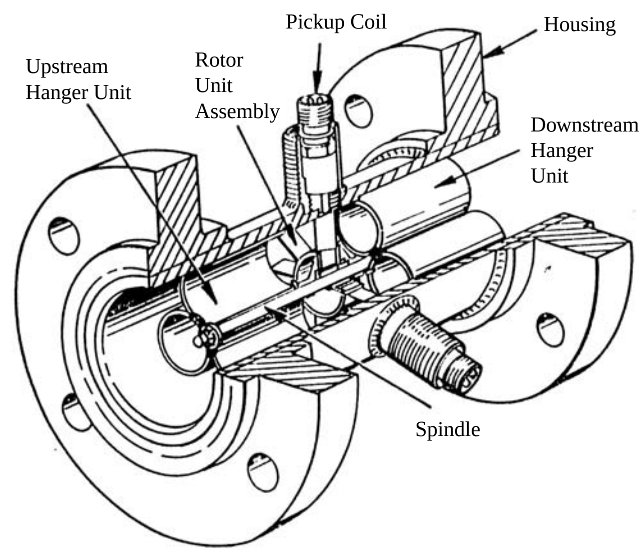


FIG. 2.25a
Cutaway view of a typical turbine meter.

With the inductance pickup coil system (see Figure 2.25b), the permanent magnet is embedded in the rotor. As the magnet rotates past the pickup coil position, it generates a voltage pulse for every complete revolution of the rotor.

The typical operating temperature range for standard pickup coils is –58 to 300°F (–50 to 150°C). Specially modified

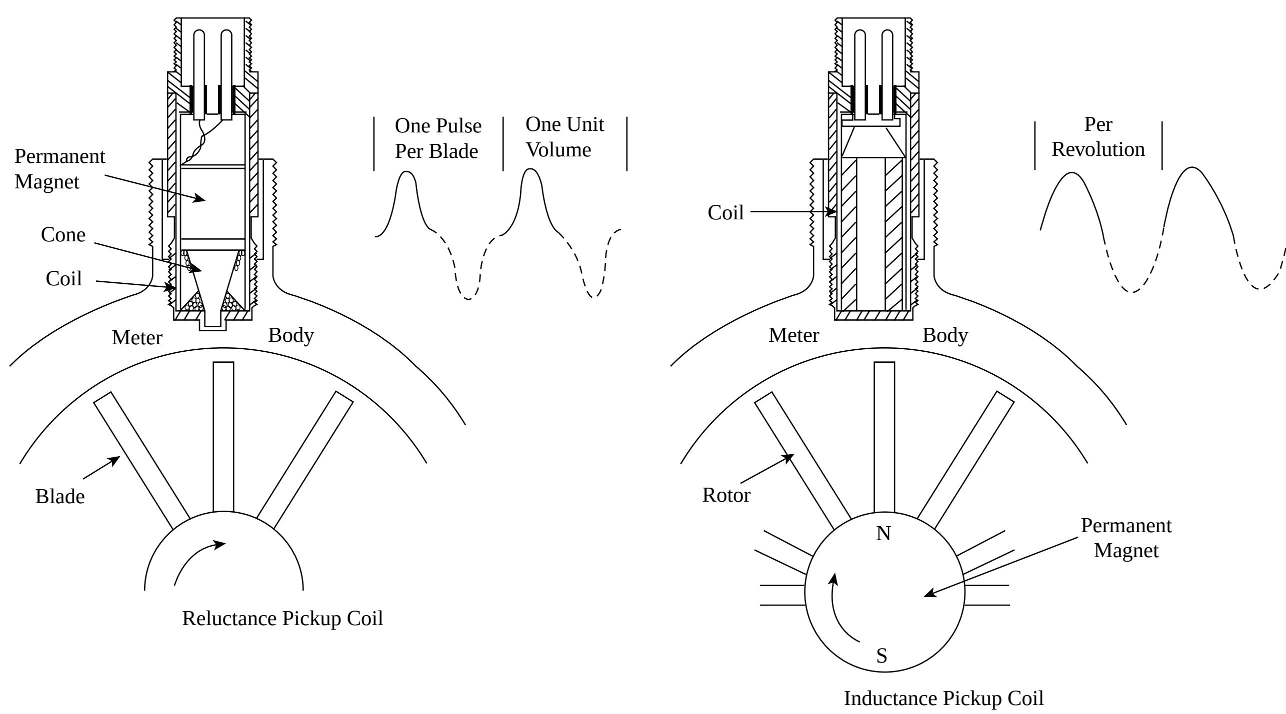


FIG. 2.25b
Alternative signal generation systems.

pickup coils are available, however, to cover operation at temperatures ranging from –328 to 840°F (–200 to 450°C). If the meter is located in a hazardous area, the pickup coil can be mounted in a flameproof or explosion-proof conduit box or, alternatively, an intrinsically safe pickup coil can be used in conjunction with zener barrier to provide an inherently safe system.

Electronic Display Units

The output signal from the turbine meter is a continuous sine-wave voltage pulse train with each pulse representing a small, discrete volume of fluid. Associated electronic units display total volumetric flow or flow rate and perform preset batching, control, automatic temperature correction, and other functions.

Most turbine meter systems incorporate a totalizer unit with a factorizing and scaling function. The pulse output from the turbine meter is not in direct engineering units. For example, each pulse might represent 0.001231 gal. The factorizer is set to this value, and the incoming pulses are multiplied by 0.001231. The display presented is then in gallons.

Alternatively, the totalizer can be a preset batch unit for automatically dispensing predetermined quantities of liquid. The required value is preset, and the totalizer then counts down to zero and provides an output (that is, contact closure) to operate a valve and terminate the batch. To provide better system repeatability and avoid hydraulic shock, the preset batch unit can be fitted with an advance warning contact, or it can incorporate a ramp function. In the former case, an output is provided, typically 2 to 5% before batch completion. This output partially closes the valve and the batch is "topped off" at a low flow rate up to the final preset quantity. The latter system includes a ramp function in the preset batch unit, providing an analog output signal at the start of the batch to open the valve at a predetermined rate. As the batch nears completion, the valve is progressively closed down to a low flow rate. The final valve closure signal is then given at the preset batch size.

Turbine meters volume flow at actual operating conditions. Consequently, if high accuracy is required, and the fluid temperature is subject to variation, automatic temperature correction is necessary. This involves measuring the liquid temperature with a platinum resistance thermometer and providing an analog control signal proportional to temperature. The temperature/volume relationship for the metered liquid is built into the automatic temperature correction (ATC) unit. Depending on the measured temperature, the ATC unit modifies the totalizer volume reading in accordance with the preset temperature coefficient of the liquid to give volume readout at the required reference temperature.

To safeguard against interference or lost pulses during signal transmission, a pulse comparator is often used on high-accuracy systems. This involves using two pickup coils (A and B) and taking two separate signal leads to the electronics. The pulse comparator unit monitors the two signals for integrity. If any pulses are lost or picked up on either line, the correct pulse sequence (A, B, A, B, A, B, and so on) will be interrupted. Any such false pulses are logged and the associated totalizer reading corrected accordingly.

Most turbine meter systems require flow rate indication or an analog control signal. These options can generally be provided from the basic totalizer unit.

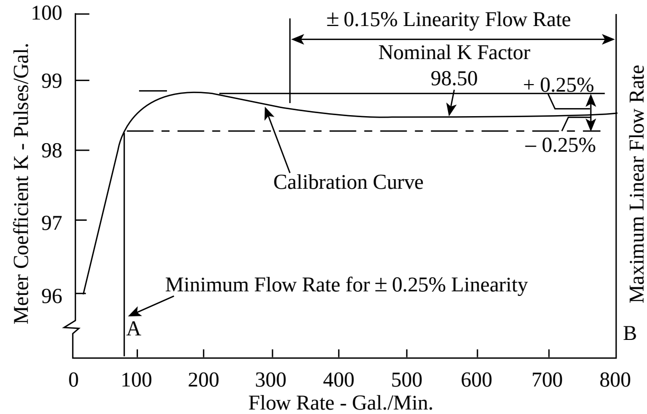


FIG. 2.25c
Typical calibration curve for a turbine meter.

Linearity and Repeatability

The nominal K factor (the number of pulses per unit volume) is primarily determined by the size and type of turbine meter. In practice, the actual K factor varies slightly between apparently identical meters due to manufacturing tolerances. Consequently, it is essential to calibrate each meter to establish its own specific K factor. A typical turbine meter calibration is shown in Figure 2.25c.

The graph is a plot of K factor against flow rate. It will be noted that, over the flow range A to B GPM, the K factor is a constant within the linearity tolerance band. The linearity tolerance band is typically ±0.25% of point over a 10:1 flow range for meters 0.75 in. (20 mm) and larger and ±0.5% of point over a 5:1 or 8:1 flow range on meters smaller than 0.75 in. (20 mm). It is important to note that the linearity is specified as "of point" or "of actual reading" and is not "of full-scale deflection."

The calibration in Figure 2.25c has a typical turbine meter hump in the low flow region (the lower 30% of the flow range). If this region is avoided, the turbine meter linearity can be improved to ±0.15% on the larger meters and ±0.25% on the smaller meters.

The repeatability of the turbine meter is typically ±0.02% of point at any flow rate within the linear range of the meter.

Viscosity and Density Effects

The principal fluid parameter that affects a turbine meter is viscosity. High viscosities change the nominal K factor and cause the calibration curve to fall away at a higher minimum flow rate (see Figure 2.25d). This causes a deterioration in the

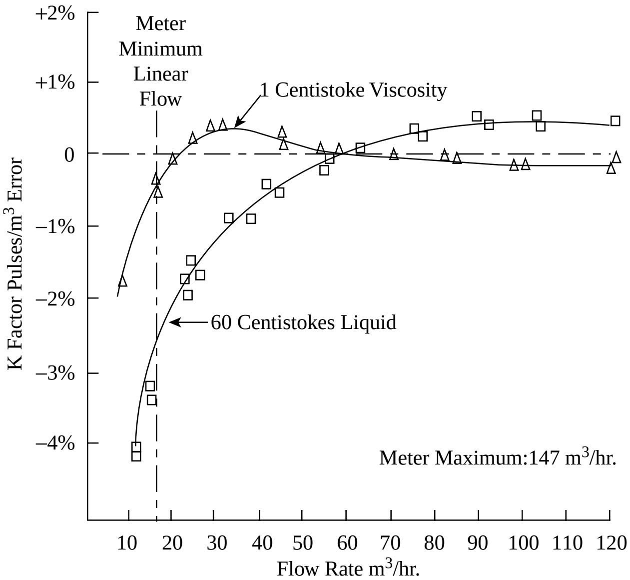


FIG. 2.25d
Calibration curves illustrating the effect of high viscosity on meter performance.

TABLE 2.25e
Typical Flow Capacity for a Range of Turbine Meters

Nominal Diameter		*Minimum Linear Flow*		*Maximum Linear Flow*	
Inches	*mm*	*GPM*	*m^3/h*	*GPM*	*m^3/h*
0.75	20	2.5	0.68	25	6.8
1	25	3.3	0.90	50	13.6
1.5	40	7.2	1.96	108	29.5
2	50	20	5.45	160	43.6
3	75	60	16.3	400	109
4	100	180	27.2	1000	272
6	150	250	68.1	2000	545
8	200	415	113	4150	1130
10	250	715	195	6400	1750
12	300	1025	280	9160	2500
14	350	1210	330	10,800	2950
16	400	1830	500	14,650	4000
18	450	2310	630	18,500	5050
20	500	2930	800	24,000	6540

linearity tolerance over the full flow range or, alternatively, a shorter usable flow range at the standard linearity tolerance.

The effect of viscosity cannot be easily quantified, because it depends on the size and type of turbine meter. In general, larger meters are less affected by viscosity than are smaller sizes. This does not imply that an oversize meter should be used on a viscous application. In fact, quite the reverse is true. On a high-viscosity application, it is advisable to size the meter so that its maximum permitted flow rate is as close as possible to the application flow rate. Thus, by tending to undersize the meter, the nonlinear portion of the calibration is avoided, and the best possible flow range is achieved.

The above comments about viscosity are applicable to the linearity of the meter. Turbine meter repeatability will not be affected in this way, and the standard repeatability tolerance will still be maintained at high viscosities. Consequently, a turbine meter can be used for such duties as on–off control on very viscous products. The control points can be determined impartially, and the meter will then repeat these readings even though its calibration may be completely nonlinear. To achieve reliable repeatability, the operating conditions must be constant.

Density has a small effect on the turbine meter's performance. On low-density liquids, the meter's minimum flow rate is increased as a result of the lower driving torque, but the change in density has a minimal effect on the meter's calibration.

Meter Sizing

Turbine meters are sized by volumetric flow rate. Each meter size has a specified minimum and maximum linear flow figure, and the meter normally should not be used outside these values. Typical flow capacities for a range of turbine meters from 0.75 in. (19 mm) to 20 in. (508 mm) are shown in Table 2.25e.

When sizing the meter, it is recommended that the maximum flow rate of the application should fall at approximately 70 to 80% of the maximum flow rate of the meter. This results in a good flow rangeability (about 8:1), and yet there is still approximately 25% spare capacity to allow for future expansion in production or increased metering requirements. Exceptions to this rule of thumb are applications that demand maximum rangeability, high-viscosity applications that demand maximum rangeability, and high-viscosity applications.

To achieve optimal performance and flow range, most turbine meters are designed for a maximum velocity of 30 ft/s (9.14 m/s). This velocity is higher than the velocities that exist in typical process pipelines, which are typically 7 to 10 ft/s (2.13 to 3.05 m/s). Consequently, if the turbine meter is the same size as the pipeline, the meter flow range will be limited to approximately 2:1 or 3:1. Hence, it is important to size the turbine flowmeter on the basis of volumetric flow rate and not on the basis of pipe diameter. If the turbine meter is sized on volumetric flow rate, it will end up to be smaller than the pipe size. This is a perfectly acceptable and normal practice if the meter is installed with the appropriate upstream and downstream straight pipe lengths and cone-type reducers (see Figure 2.25f).

Another aspect that must be considered when sizing the meter is available line pressure. Turbine meters have a typical pressure loss of 3 to 5 PSIG (20.7 to 34.5 kPa) at maximum meter flow rate. The pressure loss reduces with the square of flow rate. Consequently, if the meter is operating at 50% of maximum capacity, the pressure loss is 25% of that at maximum flow rate.

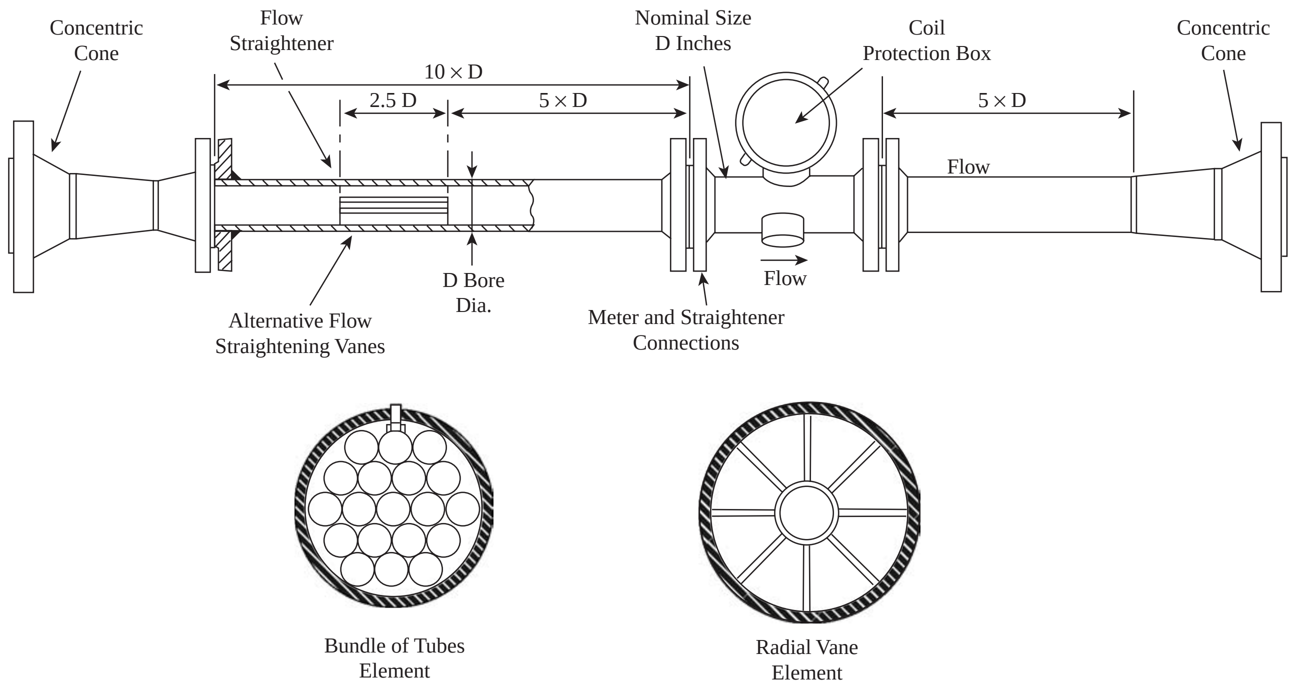


FIG. 2.25f
Recommended turbine meter installation pipework.

A typical pressure distribution through a turbine meter is shown in Figure 2.25g. As will be noted, the minimum pressure point occurs in the region of the rotor, with a substantial pressure recovery occurring immediately thereafter. It is essential to provide sufficient line pressure to prevent liquid cavitation or gassing in the rotor region. To ensure that cavitation does not occur, the downstream line pressure must be at least twice the net meter pressure loss plus 1.25 times the vapor pressure of the flowing fluid at its maximum operating temperature. When the backpressure on the meter is insufficient to meet this requirement, either the backpressure should be increased, or a larger meter operating in a lower region of its flow range (with a resultant lower pressure loss) should be considered. The meter flow range will be reduced by this approach.

If cavitation occurs, it will cause an error in the meter output, and the meter will read high. If severe cavitation is present, it will destroy some of the metallic parts and will cause serious overspeeding of the rotor, resulting in possible mechanical damage to the rotor and bearing.

Pelton Wheel Meters

It is not practical to make turbine meters for very low flow rates below 0.25 GPM (1.58×10^{-5} m^3/s). Pelton wheel meters have been developed for these very low flow rates. The meter has a small orifice that projects the liquid onto a small Pelton wheel. The velocity of rotation is then measured electromagnetically, and a frequency output signal produced. By varying the diameter of the orifice, a range of flow rates can be covered

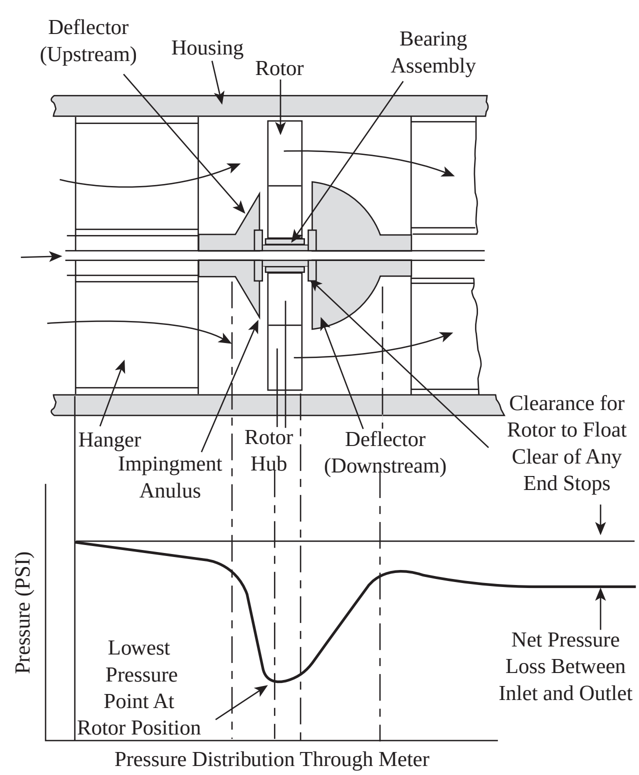


FIG. 2.25g
Typical pressure distribution through a turbine meter.

from 0.001 GPM through to 2 GPM (6.3×10^{-8} to 1.26×10^4 m^3/s). Flow range varies with meter type but is generally between 10 and 20:1. The meters offer good repeatability (±0.1%) but are generally nonlinear and have a high pressure loss, typically 15 to 20 PSIG (103 to 138 kPa). Typical applications for this type of device are metering internal combustion engine fuel flows in test rigs and additive dosing.

Meter Characteristics and Features

The wetted materials of a turbine meter are generally stainless steel throughout except for the bearing. The most widely used bearings at present are tungsten carbide or ceramic sleeve bearings, which offer exceptional reliability and immunity to wear. These materials provide good corrosion resistance capability on a wide range of process liquids (Figure 2.25h). Where these materials are not suitable, other, more expensive possibilities, such as Hastelloy® C with PTFE bearings, are feasible. On clean liquids, some meter designs use ball race bearings to achieve greater rangeability.

Turbine flowmeters have also been manufactured without bearings (Figure 2.25i). In this design, the hydraulic forces of the flowing fluid kept the dual turbine in a suspended, "hovering" state. This meter is no longer being manufactured but is mentioned here because of the interesting concept behind its operation.

In very small sizes (under 1 in. or 25 mm), a single turbine can also be rotated without having any physical contact to the meter body. In the design shown in Figure 2.25j, the process fluid enters as a tangential jet and spins and stabilizes the turbine as it exits through the center of the rotor. The speed of rotation is detected optically by a photodetector. In the 8 cm^3/m to the 8 GPM (330 l/min) flow range, up to 30:1 rangeability is claimed.

Turbine meters are suitable for extremes of temperature. When appropriate pickup coils and bearings are selected, turbine meters can operate at temperatures varying from –328°F (–200°C) to 840°F (450°C). The turbine meter housing is a very good pressure vessel, because there are no tappings or protrusions into the meter bore. Consequently, most small

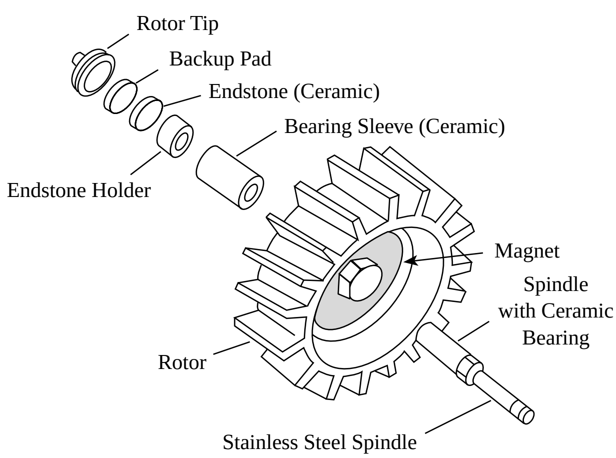


FIG. 2.25h
Ceramic bearings. (Courtesy of Badger Meter Inc.)

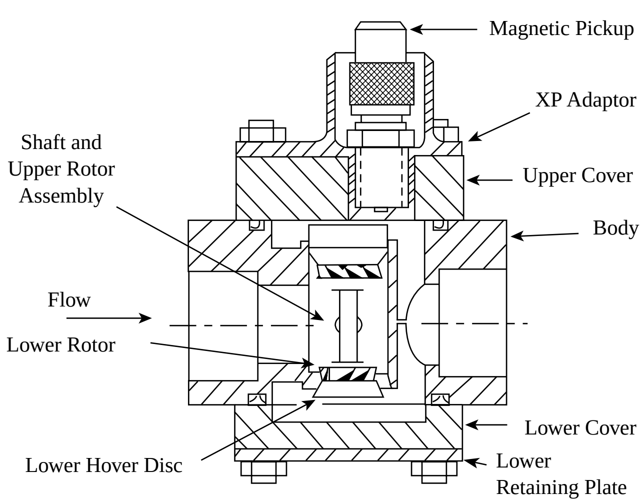


FIG. 2.25i
Bearingless turbine flowmeter. (Discontinued.)

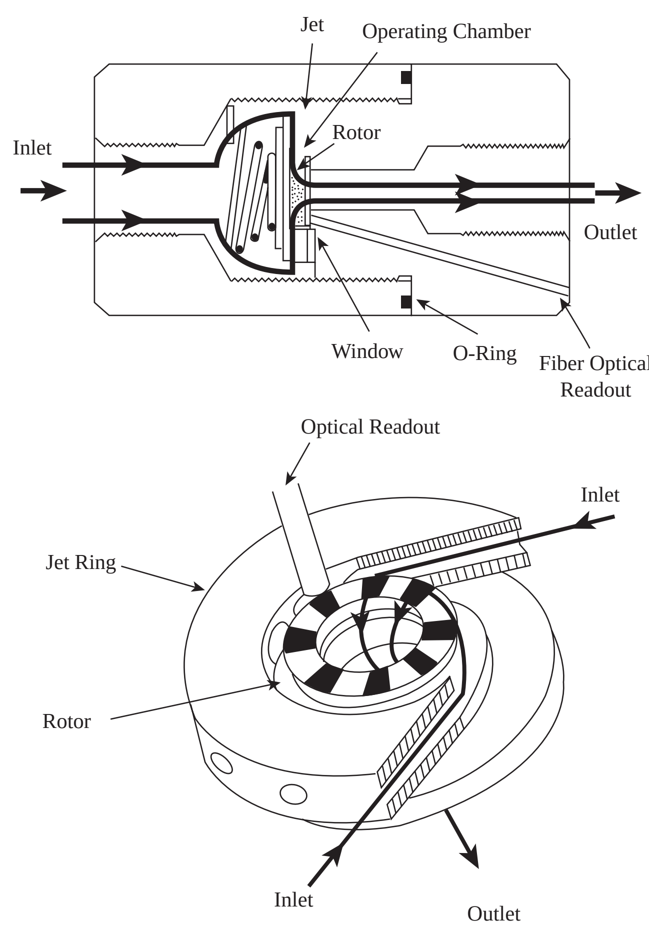


FIG. 2.25j
Unsupported single rotor with optical readout. (Courtesy of Miniflow Systems Inc.)

turbine meters are suitable for operating pressures up to 5000 PSIG (34.5 MPa), subject to the pressure limitation on the flanges or other end connections.

Another significant feature of the turbine meter is that it has a high throughput for a given size and is small in size and weight relative to the pipeline. Consequently, turbine meters can handle large-volume flow rates with a minimal requirement for space without needing special mounting stands or pads. Other features of the turbine meter include fast response time, suitability for hygienic applications, linear digital output, ease of maintenance, and simple installation.

The main limitations of the turbine flowmeter include high cost; limitation to clean and nonviscous services; the error caused by viscosity and density changes; the requirement for filtration and for 15 to 20 diameters of straight upstream pipe; the need for periodic recalibration (at operating conditions) and maintenance because the moving components are subject to wear; the potential problems of gassing, cavitation, and overspeeding; the need for relatively high backpressure; and the need for secondary components in providing a readout.

Due to its excellent performance characteristics, the turbine meter is widely used for high-accuracy royalty and custody transfer of crude oil, refined hydrocarbons, and other valuable liquids. Turbine meters are used throughout the petrochemical industry for many other applications, such as process control metering, blending, and pipeline leak detection. Turbine meters are also used in other industries for a broad range of applications, flow rates, and duties. More specialized applications include measurement of cryogenic liquids (liquid oxygen and nitrogen), high-pressure water injection to oil wells, aircraft fuel metering, test rig duty, and road tanker filling. Some of these applications require modified or special meters (for example, aircraft meters are made from aluminum alloy to save weight), but fundamentally the same meter is used in all cases.

Mechanical Installation

The turbine meter's high accuracy can be easily negated by a substandard installation. Upstream disturbances such as bends, valves, or filters may cause swirl and/or a nonuniform velocity profile, which, in turn, affects both the linearity of the meter and the nominal K factor. The errors may be positive or negative, depending on the direction of the swirl. If there is sufficient straight pipe between the disturbance source and the meter, the fluid shear or internal friction between the liquid and the pipe wall will condition the flow to an acceptable degree. The length of straight pipe required depends on the upstream disturbance and, in some instances, may have to be as long as 50 times the nominal meter diameter.

To avoid excessively long straight lengths of pipe, an internal flow-straightening element is generally used if good accuracy is required. The flow-straightening element may be a bundle of thin-wall tubes or a series of radial vanes inserted longitudinally in the upstream section of the straight pipe. The location of the vane is important; the recommended position is shown in Figure 2.25f. When a flow-straightening element is used, the upstream straight pipe requirement is reduced to 10 times the nominal meter diameter. The required downstream length is 5 times nominal meter diameter. Nevertheless, it is good practice to avoid installing the meter downstream of any severe source of disturbance, such as regulating control valves, whenever possible.

TABLE 2.25k
Typical Strainer Recommendations for Turbine Meter Installations

	Recommended Strainer			
Turbine Meter Size (Inches)	*U.S. Sieve No.*	*Wire Size (Inches)*	*Meshes/ Linear Inch*	*Opening (Inches)*
½ and smaller	120	0.0034	120.48	0.0049
¾ to 1 ½	45	0.0087	44.44	0.0138
2 and larger	18	0.0189	17.16	0.0394

If the meter is smaller in diameter than the process piping, 15° inclined angle concentric cones should be fitted at either end of the metering piping as shown in Figure 2.25f. Care should be taken with the internal alignment of all flange joints in the metering section; no gaskets should protrude into the fluid path.

To avoid mechanical damage to the turbine meter and to ensure optimal life, a suitable mesh strainer should be fitted upstream of the meter. The recommended mesh size depends on the size and type of turbine meter, but typical guidelines are given in Table 2.25k. Close attention should be paid to any application in which there are fibrous particles in the fluid. Contaminants of this type are frequently not removed by the strainer; the fibrous strands tend to wrap around the rotor and bearing, causing the rotor to slow down and the calibration to change.

Electrical Installation

The output frequency from a typical turbine meter pickup coil varies in frequency and amplitude with flow range. At low flows, the signal may be as small as 20 mV peak to peak. Consequently, if the turbine meter and electronic readout equipment are not from the same manufacturer, care must be taken to ensure that the two units are compatible with regard to pulse shape (sinewave or squarewave), signal frequency, and pulse amplitude and width.

Careful attention should also be given to the cable routing between the turbine meter and the electronics. Areas of electrical noise should be avoided, cable lengths should be kept as short as possible, impedance matching should be verified, and the appropriate shielded cable should be used. When long transmission distances are involved or the area is electrically noisy, a preamplifier should be fitted to the meter (see Figure 2.25l).

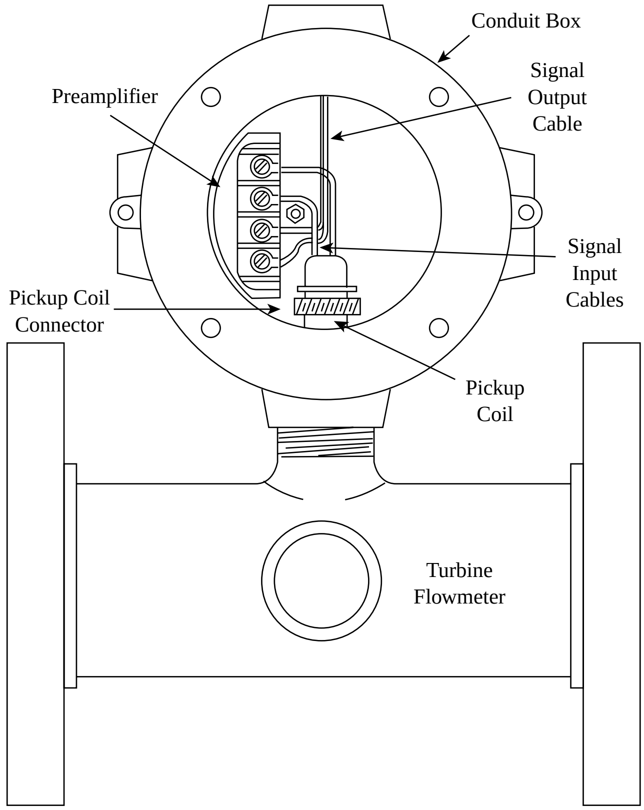


FIG. 2.25l
Complete turbine flowmeter assembly showing pickup coil and preamplifier.

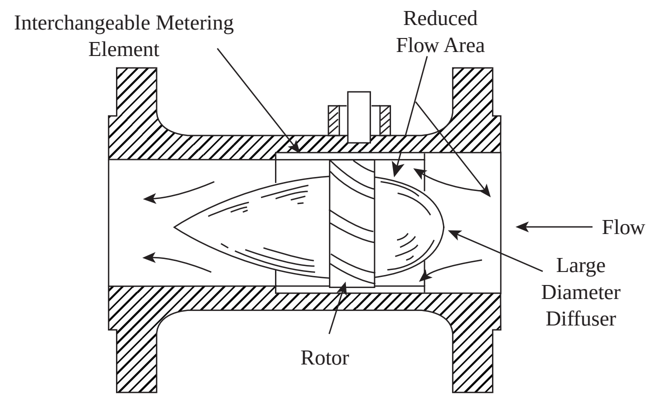


FIG. 2.25m
Typical gas turbine meter showing low ratio rotor annular-to-pipe area.

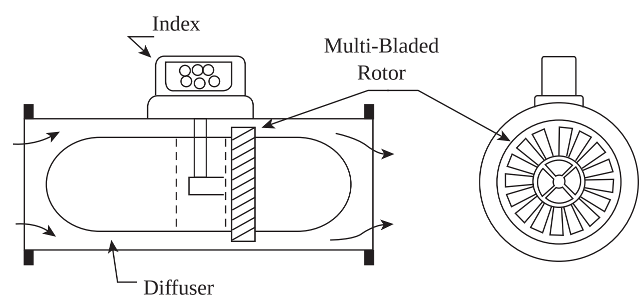


FIG. 2.25n
The axial flow gas turbine meter.

The preamplifier output signal amplitude is independent of flow rate and is typically a 12-V squarewave signal. This high-level signal can be transmitted for great distances, typically 15,000 ft (4572 m) and is far more immune to electrical interference than an unamplified pickup signal. The limitations of a preamplifier include increased cost and the necessity for a DC power supply at the meter. In some designs, an additional cable is required (a three-wire system as opposed to a two-wire system), and the ambient temperature is typically limited to 212°F (100°C).

GAS TURBINE METERS

The operating principle of the gas turbine meter is the same as already described for the liquid turbine meter. The major difference is that, as a result of the much lower density of the gas, the available fluid driving torque is greatly reduced. Consequently, gas turbine meters feature various design changes to enable the meter to operate at higher fluid velocities and to compensate for the lower driving torque. The principal changes are the use of larger hub diameters to give a smaller ratio of rotor annular area to pipe area (see Figure 2.25m), lightweight rotors, increased number of blades, modified blade angle, and alternative bearings. Some designs feature local mechanical volume flow indication and employ reduction gears in the rotor driving external gears via a magnetic coupling.

Gas turbine meters find application in fuel and other gas measurement applications because of their simplicity and wide rangeability. Figure 2.25n shows the principle of the axial flow gas turbine meter. A flow diffuser increases the flowing gas velocity and directs it to a multibladed rotor mounted in precision bearings. The calibrated index is driven by the rotor through suitable gearing. Gas turbine meters are available in sizes from 2 to 12 in. pipe diameter (50 to 305 mm) and flow ratings up to 150,000 ft^3/h (4500 m^3/h). A desirable characteristic of gas turbine meters is their increase in rangeability at elevated operating gas pressures. Rangeabilities in excess of 100:1 are attainable in large meters operating at 1400 PSIG (9.7 MPa).

As a result of the lower driving torque of the gas, it is essential to keep bearing frictional resistance to a minimum. The liquid turbine meter journal bearing is usually replaced by a ball race bearing. Any change in the bearing frictional resistance will result in a change in the meter calibration. Meters are frequently used in dust-laden gases, and the ball races are frequently of the sealed, self-lubricated type. Some designs, however, use gas bearings.

It is essential to calibrate the gas turbine meter initially, preferably under simulator operating conditions, to establish

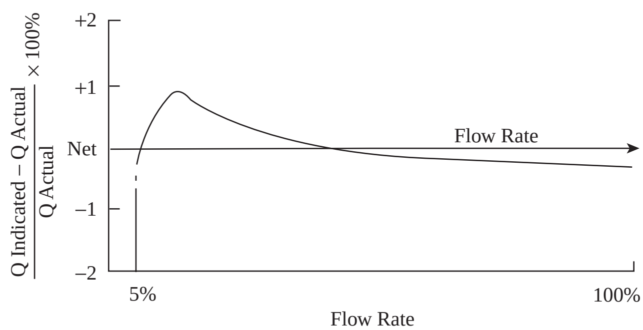


FIG. 2.25o
Typical gas turbine flowmeter calibration.

its own specific K factor. A typical calibration curve is shown in Figure 2.25o. Linearity is normally ±1% of actual flow over a flow range of 20:1. Gas turbine meters have specific minimum and maximum volumetric flow rate values, and it is essential to select the meter on the basis of these volumetric flow rates and not on the basis of the pipe size. The meter must be sized on the basis of actual volume flow and on the basis of standard reference units.

The turbine meter output frequency is proportional to the volumetric flow rate at the actual operating pressure and temperature. Pressure and temperature correction are required to convert the meter output into volume flow at reference conditions. If readout in mass units is required, either pressure and temperature correction can be used (although it does not compensate for variations in the composition of the gas) or the meter reading can be multiplied by a density gauge reading to give true mass flow.

In any compensation system, the volume and pressure or density should be measured at the same flow rate. The gas turbine meter has a typical pressure loss of one velocity head $[0.5(\rho V^2/g)]$ and a similar pressure distribution as that of the liquid turbine meter shown in Figure 2.25g. Consequently, if the pressure or density measurement is not taken at the rotor, a slight correction factor may be necessary to relate the measured value back to that pertaining at the rotor position.

Gas turbine meters are less sensitive to damage by grit and dust particles than are other positive-displacement meters. Gas turbine meters can also operate at higher pressures and have a high flow-rate capacity for a given meter size. In addition, if the meter fails, the gas flow is not obstructed, ensuring continuity of flow. Typical upstream pipe requirements are 20 times the nominal meter diameter.

Because of possible variations in the meter-bearing characteristics, calibration checks should be made at regular intervals if optimal performance is to be achieved.

TWIN-ROTOR TURBINE METERS

The single-rotor design of the turbine meters dates back to the early 1950s, when the United States aerospace industries began to use such meters extensively. At that time, they were not widely used in the process industries, because they were limited to clean services and considered somewhat fragile and therefore not always reliable. Even today, the twin- or dual-rotor turbine meter design is not well known outside the aerospace industry. The *twin-turbine* design uses two identical turbines. The *dual-turbine* design uses two turbines of different designs. The three suppliers listed in the feature summary at the beginning of this section offer three different design variations and also differing capabilities and operation.

History

By the late 1950s and early 1960s, the single-rotor turbine meters, which were used for their high accuracy and repeatability in aerospace fueling applications, were often overspun by flashing cryogenic fuels, resulting in bearing failure, and sometimes even in the loss of the turbine rotor. Such rotor losses could lead to engine failures if the turbine rotor enters the engines. This was clearly unacceptable.

Therefore, a design was needed, which in addition to extremely high accuracy over very wide flow ranges would also offer ruggedness, decrease bearing wear and improve reliability and calibration longevity. The solution was the twin rotor design, which is provided with a housing designed for 3000 PSIG (208 bar) working pressure. The actual operating pressure can be less, because it is limited by the pressure ratings of the end fittings. Special versions have been used in applications up to 40,000 PSIG (2777 bar). The meter can be used from cryogenic liquid hydrogen temperatures up to temperatures greater than 750°F (400°C). The flow sensor body and all major components are manufactured from stainless steel.

Thus, the two-rotor turbine meter was developed primarily to help overcome bearing wear and overspeeding and to provide wider flow turndown or rangeability. These same attributes are also useful in process industry applications. The twin-rotor turbine meters are capable of limiting the error to 0.1% of actual flow and providing a precision of 0.01% of reading. Their turndown can be 200:1 up to 500:1 on volumetric liquid flow applications and up to 1000:1 on gas or vapor mass flow applications.

Twin-Rotor Design

The twin-rotor design dates back to 1959, when it was used only for aerospace and military applications. In the 1970s, some major chemical companies had also started to use them for leak detection and pipeline accounting. This design withstands the flashing of fuel propellants, launch vibration, and shock while providing high-precision signal conditioning electronics. Applications included physiological measurements by NASA, where it was used to monitor astronaut breathing and urine flow during space missions. Military applications included their installation on jet engine test stands and on interservice flow transfer applications under U.S. Navy/NBS auspices. The QDI meter (as it is referred

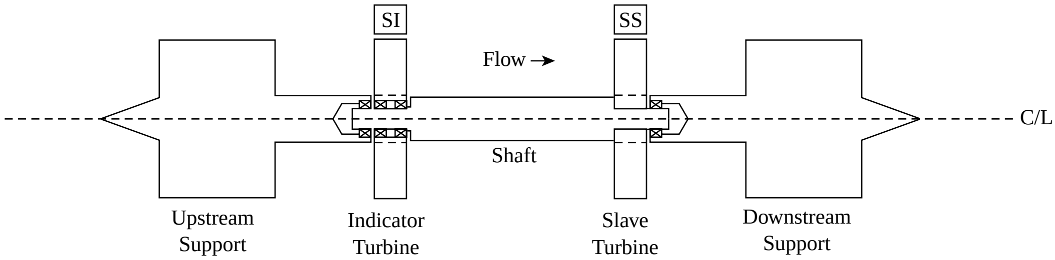


FIG. 2.25p
Twin turbine flowmeter initially designed for aerospace applications to provide long life, high rangeability, and accuracy. (Courtesy of Quantum Dynamics Inc.)

to, using the abbreviation of the manufacturer's name) is also used in flowmeter "prover" applications to check the calibration and accuracy of other flowmeters.

The QDI twin-turbine meter (Figure 2.25p) utilizes two identical turbines mounted on a single shaft, as follows:

- The downstream *slave* turbine is rigidly affixed to the sensor shaft, which rotates within the flow sensor on precision ball bearings. The bearings may use either stainless-steel alloy balls or specialty ceramic balls. Thus, the flow drives the "slave" turbine along with the flow sensor shaft.
- The upstream *indicator* turbine corotates on the driven shaft in the same direction as the shaft motion, thus minimizing the relative velocity between the indicator turbine and the driven shaft. This provides high rangeability while low angular velocities with respect to the shaft protect the indicator turbine bearings and provide improved dynamic response. Since the total angular velocity of the indicator turbine is distributed over the indicator turbine bearings and the corotating shaft bearings, the high rangeabilities can be achieved without deleterious bearing wear. Actual liquid volumetric flow rates are extremely repeatable over 200:1 turndowns or more where the linear correlation coefficients exceed 0.999999, whereby 1.0 indicates absolute perfect linearity. In compressible gaseous flow measurement applications, the mass flow rate turndown exceeds 1000:1.

The downstream turbine is referred to as the *slave* turbine, which performs the primary work of driving the shaft upon which the upstream *indicator* turbine bearings ride. Hence, this minimizes the latter's bearing RPM and friction and significantly improves rangeability, dynamic response, and bearing longevity.

Applications and Features The QDI twin-turbine meter uses an integral upstream flow profile control device to create a relatively flat flow profile, even in the low laminar flow regime. The use of integral upstream flow profiler allows for the use of a slim central shaft and long turbine blades. This contrasts with single-blade turbine meters, which utilize a large central body to accelerate the flow past the short turbine blades having high blade angles. Thus, the aerospace twin-turbine design also has a lower pressure drop. This is important in aerospace and cryogenic applications where high pressure drops could cause flashing.

The patented zero-drag RF pickups on both the indicator and slave turbines provide a powerful, high-reliability diagnostic tool, because redundant flow measurement is provided. In addition, bearing wear or contamination can be detected as changes in the relative velocity between the indicator and slave turbines. Since the slave turbine/shaft bearings experience the greatest prolonged rotation, they will begin to show wear long before the indicator turbine does. An advantage over single-turbine designs is that, in this design, even after bearing wear is thus detected, the indicator turbine will continue to provide accurate flow for some extended time period, thus allowing scheduled maintenance of the twin turbine flow sensor.

The slim central shaft of the twin-turbine design allows larger flow volumes to pass through the flow sensor without causing high pressure drops. The QDI flow sensor is used to measure flows at high velocities, such as in natural gas fired power plant, where the gas velocity reaches mach 0.3. In applications where measurement rangeability was previously obtained by using several orifice plates installed in parallel runs (Figure 2.15u), the QDI sensor can provide considerable cost savings by eliminating multiple meters and associated pipes and valves.

This flow sensor can also be used to measure bidirectional flows, with flow direction determined by quadrature. This capability, along with high dynamic response, was used to monitor astronauts' respiratory patterns. More recently, this capability has been used for detecting in–out flow in commercial gas storage applications such as in large holders or in underground storage caverns such as salt domes.

In the case of cryogenic liquid fuel loading systems, the same meter can handle liquid, gas, and two-phase flows. More recently, it has been successfully applied to high-accuracy petroleum and petrochemical custody transfer systems, power plant combustion control, pipeline leak detection based on mass balance principles, batch charging, and metrology applications involving high-value liquid or gas products such as ethylene, propylene, and so on.

The mechanical/electronic reliability of the standard unit, as calculated per military specifications, yields an MTBF of 2.5×10^5 t (28 yr). Using space-grade components yields an MTBF of 6.14×10^5 h (70 yr).

DUAL-TURBINE DESIGNS

Dual-turbine meters differ from twin-turbine designs in that they use two turbines of different blade angles and configurations, each rotating on its own bearing systems on its own shafts. These designs are more susceptible to bearing damage due to overspeeding than are the twin-turbine units, and care must be taken not to subject such flow sensors to excessive flow velocities.

Dual Turbines Rotating in the Same Direction

In the 1960s, Rockwell International was studying the problems of wear and the associated loss of accuracy in turbine meters, and the company also came up with idea of using a dual-rotor turbine system to reduce the effects of bearing friction and wear. As a result, Rockwell designed its dual-turbine sensor (Figure 2.25q) primarily for clean gas services such as natural gas, and it provides adequate service life for its intended end use in the gas pipeline and distribution industries. (Rockwell subsequently sold off this dual-rotor design to Invensys Energy Metering, located in DuBois, PA.)

The size of this meter ranges from 4 in. (100 mm) to 12 in. (300 mm). Its materials of construction are normally aluminum or carbon steel. The aluminum model is rated for a maximum working pressure of 175 PSIG (12.15 bar), whereas the steel model is rated from ANSI 150 (275 PSIG or 19 bar) to ANSI 600 (1440 PSIG or 100 bar). Temperature ratings for the meters are –20 to +165°F (–29 to +74°C), but a special low-temperature steel model is also available that can be used down to –40°F (–40°C).

The rotor bearings in this meter design require lubrication. This can be done manually or at specified time or volume intervals by an automatic, meter-mounted system. Mechanically, this meter is rather complex, but the needed maintenance can be done in line if the process flow is shut down or bypassed. Precalibrated measuring assemblies can be provided for quick change-out needs. The meter is fitted with a flow conditioning inlet nose cone that reduces the straight upstream pipe length required, but damage to this nose cone can result in significant calibration errors.

Operation This dual-turbine meter uses two turbines that are located close together and rotating on two independent shafts. The upstream turbine has a high blade angle, and the downstream turbine has a very low blade angle. Since the upstream turbine blade angle is much higher than that of the downstream one, the latter will rotate at a slower angular velocity. The flow rate is measured as the difference in the speed of the two rotors. In theory, when the bearings begin to wear, the upstream turbine will spin slower, changing the fluid exit angle and causing the downstream indicator turbine to adjust its speed by an equal amount. This is claimed to adjust away bearing wear and also provide bearing diagnostics, but the validity of this claim depends on the assumption that the wear and contamination is the same on both sets of bearings.

This flow sensor has a very large central hub, which also contains the sensor's mechanical index gearing. The large hub accelerates the flow through a narrow annulus, which results in a somewhat high pressure drop. Since both the upstream and the downstream turbines rotate on a single set of bearings, the meter should not be subjected to excessive flow rates, given that this might damage the bearings. Also, this meter should not be used where slugs of condensate flow may occur, since this also will cause damage.

The inaccuracy of the meter is claimed to be ±1.0% of actual flow over the entire operating range, and the normal linearity of ±1.0% can be improved to ±0.5% if high-pressure calibration is used. The repeatability is better than 0.05%, and reproducibility is better than ±0.1%. While the above-described performance is not much superior to single-rotor conventional turbine meters on natural gas applications, this meter is more immune to positive or negative swirl, pulsation, jetting, and contamination. This meter is also autocorrecting.

Dual Turbine with Counter-Opposed Rotation

The dual-rotor turbine meter from Exact Flow is relatively new (Figure 2.25r); the company's meters date back to about 1995. It is similar to the QDI meter (Figure 2.25p) in some ways, but there are marked differences as well. These contribute to performance improvements (such as high turndowns) but also to limitations (such as being limited to liquid service only), because its bearings are susceptible to damage by overspeeding.

In this design, the two turbines have counter-opposed blade angles and rotate on a single shaft. The swirl from the upstream turbine thus impinges on the downstream one at near right angles, causing the downstream turbine to rotate faster and in the opposite direction (unlike the corotation of the QDI twin turbine). This approach improves metering rangeability by forcing the downstream indicator turbine to spin at higher RPM at low flow rates, but it can also make the bearings more vulnerable.

This dual turbine also utilizes a large central hub that constricts the flow into a narrow annulus, thus accelerating the flow past the downstream indicator turbine and promoting the onset of the turbulent flow regime in the narrow annulus. The disadvantage of this increased velocity is the corresponding increases in the pressure drop across the flow sensor.

Because each turbine is mounted on its own set of bearings, as is the case with single-rotor meters, care must be taken not to subject this meter to excessive velocities or to flashing liquid flows, because such conditions will likely result in excessive bearing wear or failure. This design is not

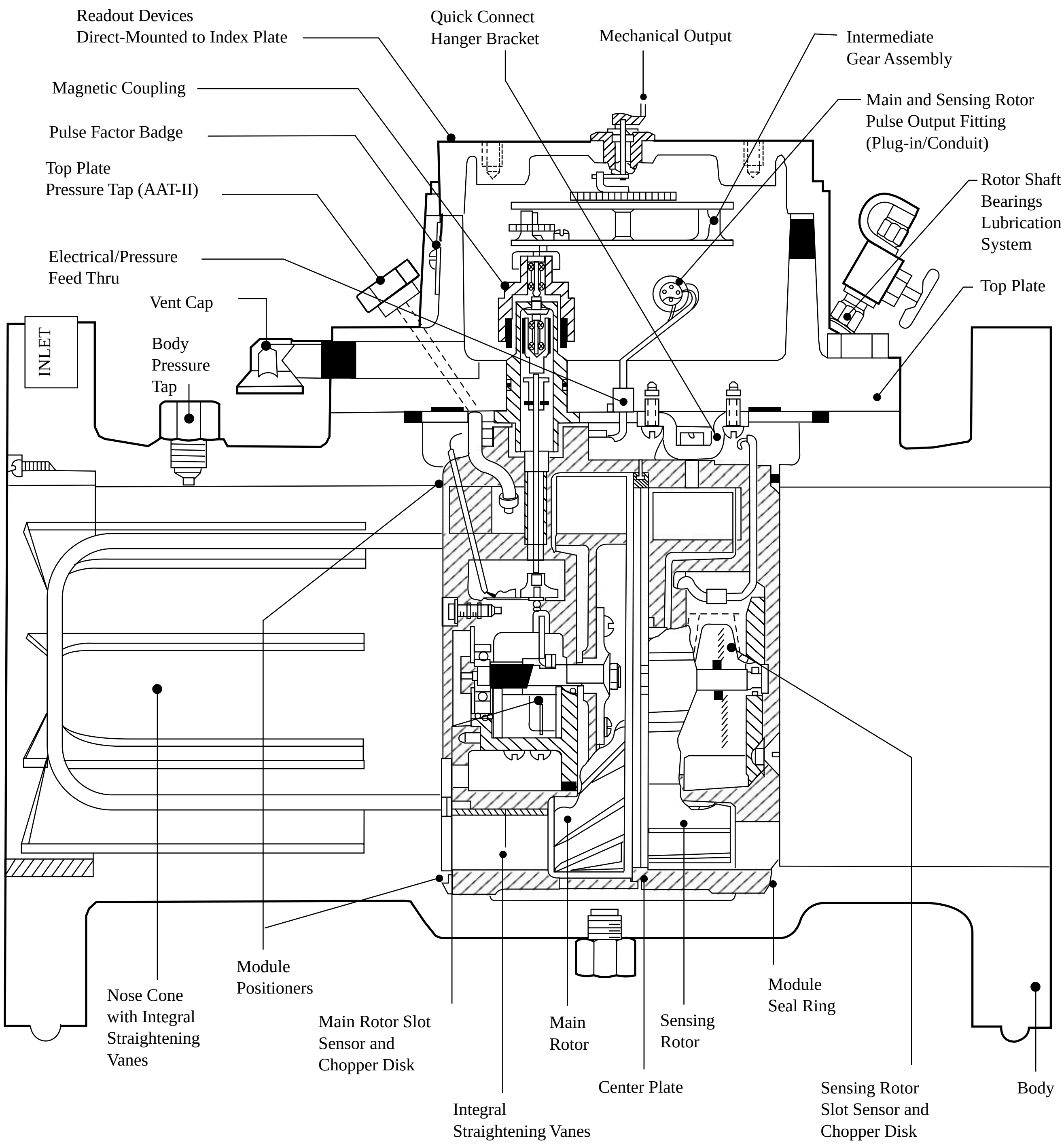
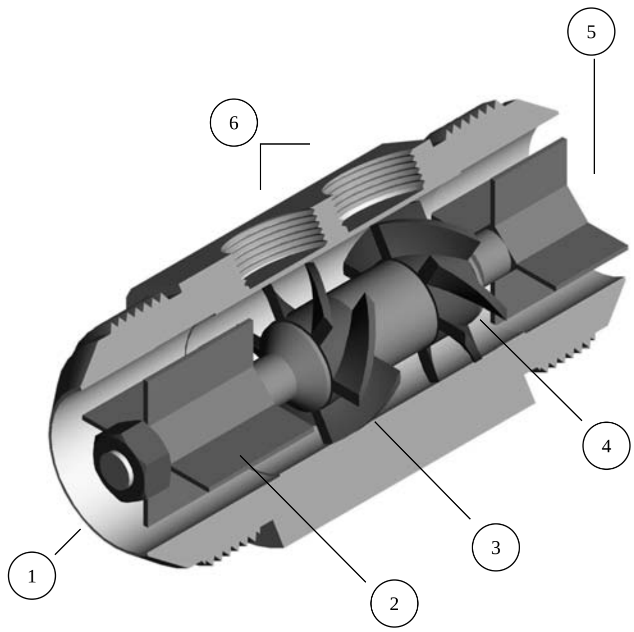


FIG. 2.25q
Auto-correcting dual-rotor turbine flowmeter used in natural gas pipeline applications. (Courtesy of Invensys Energy Metering.)

immune to overspeeding damage, and the bearing wear is also worse than with the QDI design. Both turbines in this dual-turbine flow sensor can be instrumented in the same manner as in the QDI twin-turbine sensor to provide bearing diagnostics.

Standard sizes range from 0.5 in. (12 mm) to 4 in. (100 mm), but special units up to 12 in. (295 mm) can be obtained. Essentially all ANSI pressure ratings are available, and the available operating temperatures range from –40°F (–40°C) to 450°F (232°C). Claimed calibration inaccuracy is ±0.1% of actual flow, and linearity is ±0.15 to 0.20% of rate with a typical repeatability of ±0.02%. Turndown ratio can range from 300:1 to 700:1 and, if reduced accuracy is acceptable, can reach up to 1000:1.

Principle of operation



1. Unconditioned flow enters flowmeter.
2. Straightening vanes smooth the flow as it enters the first rotor.
3. Flow transfers momentum to the first rotor making it spin counterclockwise. Flow then exits rotor with a clockwise spin.
4. Flow enters second rotor with a nearly perpendicular angle of attack thereby transferring additional momentum to the second rotor. This additional momentum results in greatly extended turndown.
5. Flow exits flowmeter.
6. A pick-up transmits the rotor frequency signal to remote instrumentation. Optional dual pick-ups transmit signals from both rotors - the sum of which is a constant for any given flowrate. This provides powerful diagnostics and swirl insensitivity. In addition, the dual rotor effect increases the turndown ratio by 10 times that of a standard single rotor turbine meter.

FIG. 2.25r
Dual-turbine flowmeter, provided with dual pick-ups and with counter-opposed turbine rotation. (Courtesy of Exact Flow Corp.)

This dual-turbine flow sensor is primarily for nonflashing liquid flow applications and is not recommended for use on two-phase flow streams. The track record of this flowmeter, as compared to the QDI, is relatively limited, given that only a moderate number of existing field applications are now in operation. Yet, because of the inherent advantages of increased reliability and rangeability resulting from having two rotors (over single-rotor designs), the numbers of both QDI and Exact Flow installations are likely to rise in the coming years.

Comparing the Three Two-Turbine Designs

QDI is the only supplier that markets only complete flow measurement systems, which include all electronics and algorithms, rather than just turbine meters. This is because their system employs proprietary designs and algorithms. They do not sell just the turbine meters—only complete and totally integrated systems. Thus, the total responsibility for the system, including documentation and warranties, comes from them. This can be a big plus. QDI is also the only turbine meter design that is qualified as a continuous U.S. Defense Logistics Agency "certified quality vendor" and by the U.S. Navy as a "quality/lowest cost of ownership" equipment contractor.

IMPELLER AND SHUNT FLOWMETERS

Another flowmeter widely used in steam and gas flowmetering and totalizing applications is the shunt flowmeter illustrated in Figure 2.25s. It consists of an orifice plate in the main flow line and a self-operating rotor assembly in the bypass.

As gas flows through the meter body, a portion of flow is diverted to drive the fan shaft assembly, which is rotating on a jewel bearing. A second set of blades on the fan shaft, rotating in damping fluid, acts as a damper or governor. Rotational speed of the shaft is proportional to the rate of flow at all rates within the normal range of the meter.

These flowmeters are available in sizes of 2 in. (50 mm) and larger. Their inaccuracy is around ±2% of the actual flow, and their rangeability is about 10:1.

Impeller- and propeller-type flowmeters are widely used in wastewater and irrigation application where large flows and line sizes (up to 48 in. or 11.2 m) are required and cost is more important than accuracy. Accuracy is claimed to be 2% of reading. As illustrated in Figure 2.25t, in this meter, a corrosion-resistant plastic impeller is connected to a flexible and self-lubricating cable, which through a magnetic coupling drives an external mechanical register without requiring gears for its operation. The register is sealed from the process and requires no external power for operating a six-digit totalizer and a flow rate indicator. Easy access and removal of the complete flowmeter is provided through a cover plate. Straightening vanes are provided to improve the flow profile. The materials of construction can be aluminum, epoxy-coated carbon steel, plastic, or stainless steel.

INSERTION-TYPE FLOWMETERS

Both the liquid and gas turbine meters described above are full-bore metering devices; all flow passes through the meter. Their cost increases proportionately with pipe diameter. The insertion

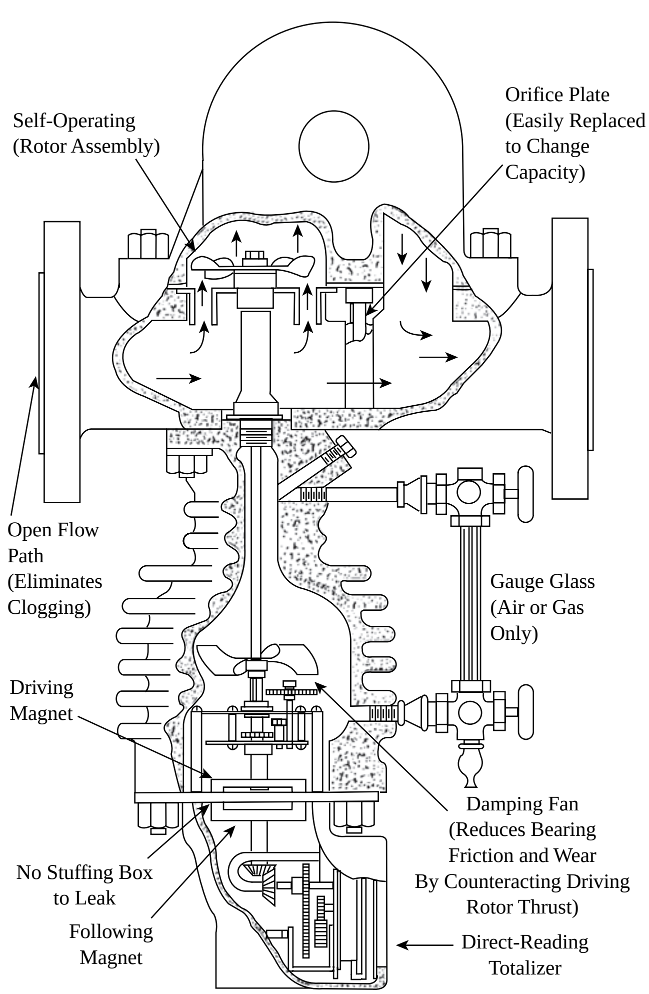


FIG. 2.15s
Shunt flowmeter.

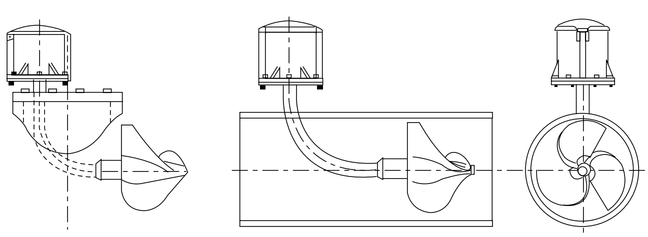


FIG. 2.25t
Impeller flowmeters are available in the paddle or the flow-through design. (Courtesy of McCrometer.)

turbine meter is a set of small turbine meter internals mounted on a probe in a large diameter pipe (see Figure 2.25u). The meter operating principles are the same as described previously except that the meter measures the fluid velocity only at a single point on the cross-sectional area of the pipe and does not "see" all the fluid. Total volumetric flow rate for the pipeline can then be inferred if certain assumptions are made about the velocity at measurement point. The velocity distribution

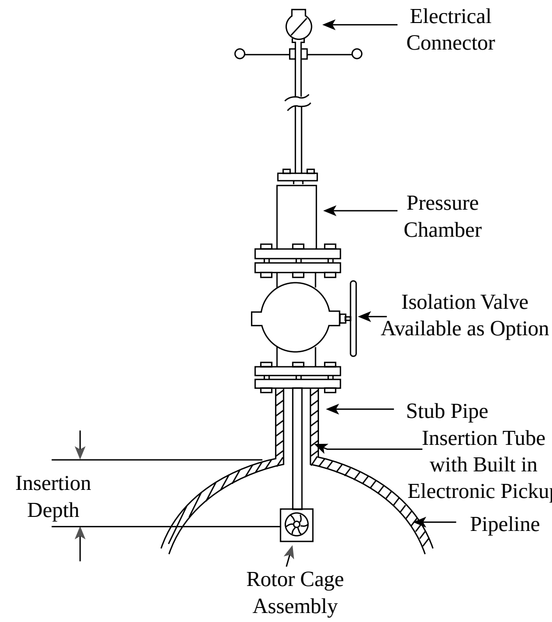


FIG. 2.25u
Insertion turbine flowmeter installed in large-diameter pipe.

can either be established by "profiling" the line (that is, taking a series of measurements across the pipeline and establishing the fluid velocity profile) or by establishing the optimal compromise insertion depth for a range of pipe diameters.

The insertion meter cannot be as accurate as a full-bore meter, since it is measuring velocity only at one point on the cross-sectional area. It does, however, provide a very low-cost metering system for large-diameter gas or liquid pipelines where accuracy is not important.

Insertion meters can be hot-tapped into existing pipelines through a valving system without shutting down the pipeline. A flanged riser, complete with valve, is welded to the pipeline. A hot-tap device is coupled to the valve, the valve is opened, and the pipe is penetrated. The hot-tap unit is withdrawn, and the valve is closed. The insertion meter is then installed, the valve is opened, and the meter is screwed in to the appropriate depth.

Insertion meters can be used on pipelines above 4 in. (102 mm) and, due to the small cross-sectional area relative to the pipe area, their pressure loss is very low. Typical linearity and repeatability figures are ±1% and ±0.25%, respectively. These are point velocity readings; in overall volumetric accuracy terms, the effects of changes in velocity profile must also be considered.

Optical Flow Sensors

A specialized version of the insertion-type turbine flowmeter is the optical photoflow sensor. The flow transducer consists of a probe supporting a low-mass rotating element that interrupts a light ray traveling from a light source to a photo transistor. The result is a pulse train that is converted into a volumetric flow representation.

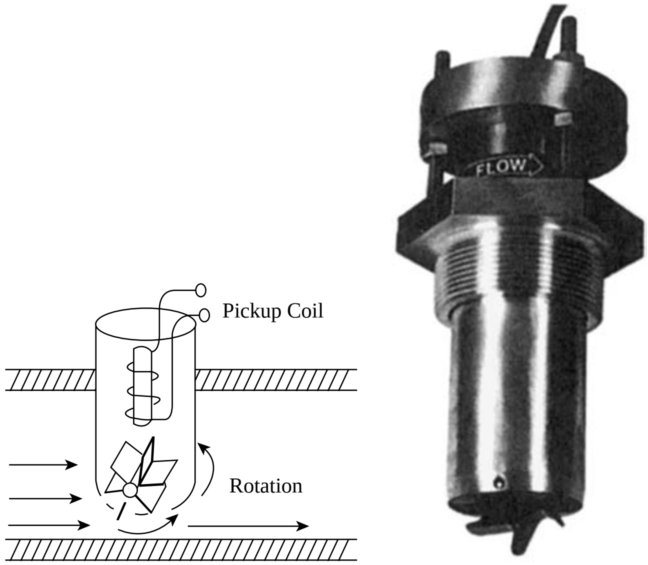


FIG. 2.25v
Paddlewheel flowmeter. (Courtesy of Data Industrial Corp.)

This flow transducer provides flow ranges as high as 100:1, bidirectional measurement without additional calibration, and extremely low pressure drop. The transmitter has only one moving part, the flow-sensing element. The bearing for the element is not located directly in the flow stream, enabling the transducer to handle severe flow conditions such as heavy surging and pulsating flows.

The installation requirements include the need for ten or more diameters of upstream straight run and the need to eliminate rotary valves (such as butterflies) at the ends of the measuring run.

Paddlewheel Flowmeters

One of the least expensive ways of measuring liquid flow in larger pipes (up to 12 in. or 305 mm) is to use one of the paddlewheel-type probes illustrated in Figure 2.25v. The rotation of the paddlewheel can be directed magnetically or optically, and the different manufacturers offer these probe units in both plastic and metallic materials. Accuracies, pressure ratings, and temperature ratings are low, but rangeability is reasonable, as these units are responsive to velocities as low as 1 ft/s (0.3 m/s) and can handle just about any maximum velocity. The fixed-insertion-length designs tend to be less accurate than the adjustable ones, as they cannot be moved as velocity profiles change. Some manufacturers claim these units to be usable on slurry service, but this is likely to require frequent cleaning.

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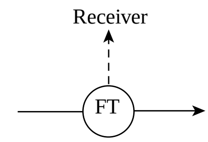
2.26 Ultrasonic Flowmeters



Ultrasonic
Flow Sheet Symbol

R. SIEV (1969) **L. D. DINAPOLI** (1982, reviewed 1995)
B. G. LIPTÁK (1995) **J. YODER** (2003)

Types	A. Transmission (contrapropagating transit time) B. Reflection (Doppler frequency shift or multipulse time shift) C. Open-channel (Note: A and B can be either “wetted” or “clamp-on.” Type A is more often wetted, type B is more often clamp-on. Clamp-on designs cannot be used as easily on concrete or lined metal pipe as on ordinary metal pipe. Type C is usually noncontacting.)
Applications	A. Clean liquids with little or no solids or bubbles; gases B. Slurries with solids (0.2 to 60% concentration, depending on particle size), liquids that are aerated or contain bubbles, gases with sound-reflecting particles, single-phase turbulent clean liquid C. Open-channel flow measurement based on upstream level in front of flumes or weirs
Flow Velocity Range	A. Normal is 1 to 50 ft/s (0.3 to 15 m/s); maximum reported is 0.1 to 100 ft/s (0.03 to 30 m/s). B. Minimum velocity for solids to stay in suspension is about 2.5 ft/s (0.75 m/s); bubbles require 6 ft/s (1.8 m/s). Otherwise, 0.2 to 60 ft/s (0.06 to 18 m/s) would be usable. C. Limits are unavailable in the literature.
Process Temperature	A and B. –300 to 500°F (–184 to 260°C); higher or lower with special sound-transmitting wedges
Design Pressure	A. Up to 3000 PSIG (207 bars) for wetted; unlimited for clamp-on B. Unlimited for clamp-on C. Usually atmospheric
Materials of Construction	A. Spools or transducer probes: steel, stainless steel, or alloys B. Usually clamp-on C. Noncontacting
Sizes	A. 0.125 to 120 in. (3 mm to 3 m) diameter B. 0.5 to 72 in. (13 mm to 1.8 m) diameter C. Not applicable
Straight Pipe Required	A and B. 10 to 20 diameters upstream, 5 downstream; very disturbed profiles require even longer straight runs or flow straighteners C. See requirements for weirs of flumes
Inaccuracy	A. From 1% of actual flow to 2% of full scale. Error can be reduced by careful determination of pipe ID and by increasing number of paths B and C. 2 to 5% of full scale
Costs	A. Spool designs in steel, not including options or special features and of the single-path design: $5000 for 4 in. (100 mm), $8000 for 10 in. (250 mm), $14,000 for 24 in.

(600 mm). Clamp-on design: $3000 regardless of size, and $1000 per acoustic coupling with thermal expansion chamber.

B. Clamp-on design, not including options or special features, is about $3000, independent of pipe size; acoustic coupling is additional.

C. $2200

*Partial List of Suppliers**

ADS Environmental Service (A)
Caldon Inc. (A)
Controlotron Corp. (www.controlotron.com) (A†, B†)
Danfoss A/S (www.danfoss.com)
Dynasonics Inc. (A, B†)
Endress+Hauser Inc. (www.us.endress.com) (A, C)
FMC Energy Systems (www.fmctechnologies.com) (A)
Fuji Electric (www.fujielectric.com)
GE Panametrics Inc. (www.panametrics.com) (A†, B†)
Greyline Instruments Inc. (www.greyline.com) (B)
Inventron Inc. (C)
Isco Inc. (www.isco.com) (C)
Krohne Inc. (www.krohne.com) (A†)
Mesa Laboratories (A, B)
Quality Control Equipment Co. (C)
Sick Inc. (www.sickoptic.com)
Siemens-Milltronics Inc. (www.sea.siemens.com) (C)
Sparling Instruments Inc. (www.sparlinginstruments.com) (A, C)
Thermo Polysonics (www.thermopolysonics.com) (A, B)
Tokyo Keiki
Yaskawa (www.yaskawa.com)

Ultrasonic flowmeters were first introduced in Japan, in 1963, by Tokyo Keiki (now Tokyo). In 1972, Controlotron became the first U.S. manufacturer to introduce them in the United States. During the 1970s and early 1980s, the process control industry had high expectations for these devices. It was anticipated that they could be used for all types of process fluids (transit-time designs for clean fluids and Doppler reflection types for dirty, slurry-type streams); they could be installed without requiring a process shutdown (clamp-on types); their prices would be unaffected by pipe size and therefore would be economical for larger pipes; and they would not generate any pressure drop and would provide wide rangeability in both directions. These expectations generally did not come true until very recently.

The image of ultrasonic flowmeters was rather tarnished for decades because the complexity of the measurement produced was not initially realized. Factors that affect the measurement include the influence of the pipe, the flow profile, and the many practical obstacles and environment interferences that can occur. For the clamp-on designs, it turned out to be difficult to maintain a good acoustic coupling that would not fail from thermal expansion or drying out of the couplant (at higher temperatures for prolonged periods) and would not short-circuit by "ringing around the pipe." These problems have now been solved, or at least well defined.

For wetted designs, failure contributions included the effect of changes in velocity profiles (Figure 2.26a), the effect of variations in the refractive index, upstream piping configurations,

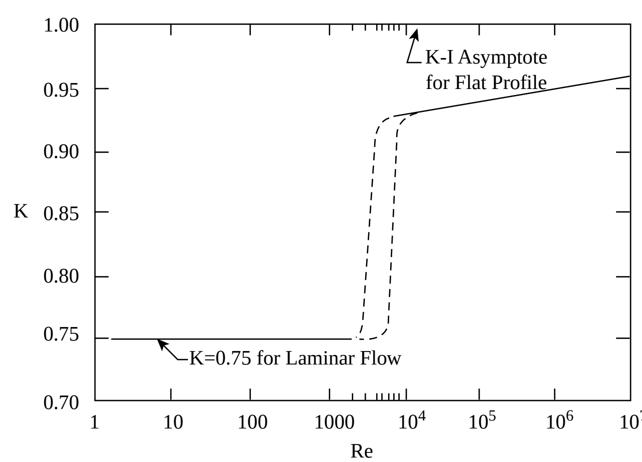


FIG. 2.26a
The ultrasonic flowmeters operate by averaging the velocity profile. This profile is flat at high Reynolds numbers and elongated at low Reynolds numbers. Consequently, the meter factor (K) also varies with Re, and it is rather unpredictable in the transition zone between laminar and turbulent regions.[1]

* Note: Most popular are units from GE Panametrics, Daniel-Emerson, Siemens-Milltronics, Controlotron, Endress+Hauser, Krohne, Thermo Polysonics, and ADS Environmental Service.
† Clamp-on design available.

making the acoustic path long enough in smaller sizes, overcoming the effects of turbulence, ambient conditions, and fluid property changes, including the change in the velocity of sound with temperature. These problems also have been solved or at least better identified.

TRANSIT-TIME FLOWMETERS

As the name implies, these devices measure flow by measuring the time taken for an ultrasonic energy pulse to traverse a pipe section, both with and against the flow of the liquid within the pipe. Figure 2.26b is a diagram of a representative transit-time flowmeter.

The time (t_{AB}) for the ultrasonic energy to go from transducer A to transducer B is given by the expression

$$t_{AB} = L/(C + V \cdot \cos\theta) \qquad \textbf{2.26(1)}$$

The time (t_{BA}) to go from B to A is given by

$$t_{BA} = L/(C - V \cdot \cos\theta) \qquad \textbf{2.26(2)}$$

where
- C = speed of sound in the fluid
- L = acoustic path length in the fluid
- θ = angle of the path with respect to the pipe axis

By combining terms and simplifying it can be shown that, for $V << C$,

$$\Delta t = t_{BA} - t_{AB} = 2 \cdot L \cdot V \cdot \cos\theta/C \qquad \textbf{2.26(3)}$$

It can also be shown that:

$$V = L \cdot \Delta t/2 \cdot \cos\theta \cdot t_A^2 = K \cdot \Delta t/t_A^2 \qquad \textbf{2.26(4)}$$

where t_A is the average transit time between the transducers.

Since the cross-sectional area of the pipe section or *spoolpiece* is known, the product of area and velocity will yield volumetric flow rate.

Frequency-Difference Type

In sing-around flowmeters, the reciprocals of transit times are used. This leads to a frequency difference (Δf) that is proportional to the flow velocity V or to the mach number V/C. The difference in frequencies is related to the velocity as follows:

$$V = \Delta f \cdot L/2 \cdot \cos\theta \qquad \textbf{2.26(5)}$$

The multipulse time-shift reflection method uses one or more pulses and times them to determine the change in range per second to an ensemble of scatterers. The change in range per unit time yields the velocity of scatterers.

Flowmeter Construction

The flowmeter usually consists of an electronics housing, transducers, and a pipe section. Several options are available as to the construction of the transducers and pipe section. Some designs allow removal of the transducers without interrupting process flow. A spoolpiece with integral transducers is one of the most common types of construction and is shown in Figure 2.26b. The manufacturer mounts the transducers to a flanged pipe section (spoolpiece). Usually, the manufacturer calibrates the unit to meet the customer's specifications. The spoolpiece thus becomes an integral part of the hydraulic system, so it is not easily retrofitted into an existing system.

Clamp-on transducers can be mounted outside an existing pipe, as shown in Figure 2.26c. The manufacturer can calibrate this type of system only if the customer provides detailed information on pipe diameter, pipe wall thickness, process fluid, percent of solids concentration, process temperature, variations in process temperature, and so forth. This type of flowmeter is easily retrofitted onto an existing system, given that no pipe section need be installed.

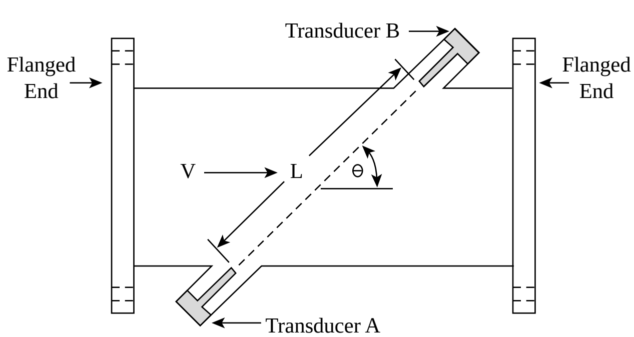


FIG. 2.26b
Transit-time flowmeter.

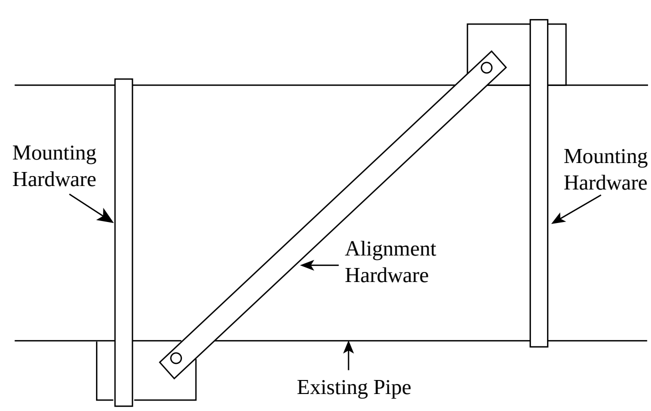


FIG. 2.26c
External transducers.

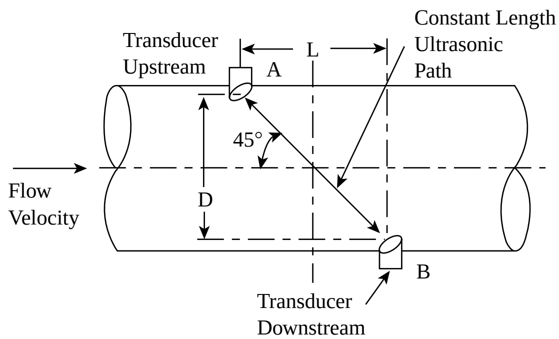


FIG. 2.26d
Wetted transducers communicate over a path that is fixed and independent of fluid speed, unless sound speed is nonuniform. (Courtesy of Panametrics Inc.)

Some manufacturers provide wetted transducers and mounting hardware that the user installs into an existing pipe. The user drills holes into the existing pipe and attaches the transducer mounting hardware by welding or other suitable means. The transducers are then mounted and aligned. Usually, the user may calibrate this type of unit after measurements of transducer angle and spacing and pipe diameter are made.

In case of "wetted" transducers, it is important to keep the distance that the ultrasonic pulse travels constant. The best way to achieve this is to keep the transmitting and reflecting surfaces perpendicular to each other (Figure 2.26d). This eliminates the effect of changes in the angle of refraction that can result from changes in process temperature or composition. Particularly in smaller pipes, the travel distance of the ultrasonic pulse might not be sufficient to produce accurate flow signals. Figure 2.26e shows how such distances can be increased.

In the early clamp-on designs, one of the difficulties was establishing an acoustically efficient sound-conductive path between the transducer and the process fluid inside the pipe. In the case of clamp-on designs, the transmitting and reflecting surfaces are the inside surfaces of the pipe. 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. The acoustic coupling between the transducer and the pipe can be improved (Figure 2.26f) by eliminating the possibility of dry-out and by allowing for thermal expansion and contraction. Unfortunately, such couplings are relatively expensive and require periodic refilling of the fluid.

Application and Performance

As with most flowmeters, the spoolpiece or pipe section must always be full to ensure proper operation and volumetric flow indication. Most manufacturers will specify the minimum distance from valves, tees, elbows, pumps, and so on

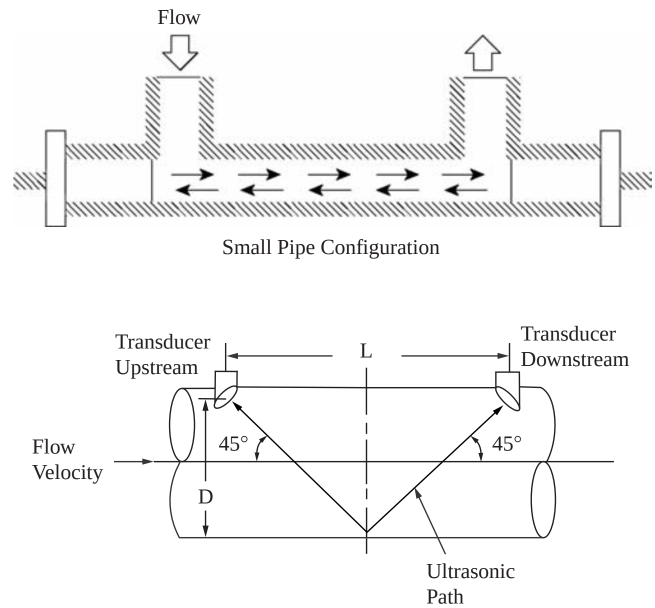


FIG. 2.26e
In smaller pipelines the time difference can be amplified by locating the transducers at the ends of a straight pipe section or by "bouncing" the ultrasonic pulse (one or more times) as shown on the right. (Courtesy of GE Panametrics Inc.)

that will ensure accurate flowmeter performance. Typically, 10 to 20 diameters upstream and 5 diameters downstream are required. The flowmeter relies on an ultrasonic signal traversing across the pipe; therefore, the liquid must be relatively free of solids and air bubbles. Bubbles in the flowstream generally cause more attenuation of the acoustic signals than do solids and therefore can be tolerated less. The flowmeter can tolerate a larger percentage of solids than bubbles.

Depending on the process fluid, proper transducer materials and protection must be chosen to prevent transducer damage due to chemical action. Process temperature limitations must also be considered for proper flowmeter application.

Accuracy is usually specified as a percent of rate. Typically, for a single-path flowmeter, it is approximately 1 to 2% of rate, depending on design, velocity, pipe size, and process. This accuracy can be expected only with calibrated flowmeters and only within the range of their calibration. Repeatability is usually specified as a percent of rate, typically about 0.5%, depending on velocity range and calibration.

To improve performance and accuracy for larger pipe sizes, some suppliers offer flowmeters with two, four, or more pairs of transducers arranged to interrogate multiple acoustic paths. The cost of such units is higher than that of a single-path flowmeter. The inaccuracy of multipath flowmeters can reach or exceed 0.5% of actual reading within a narrower range if the flow velocity exceeds 1 ft/s (0.3 m/s). Multipath flowmeters are widely used for custody transfer of natural gas. The ultrasonic market for measuring natural gas flow is the fastest-growing segment of the flowmeter market.

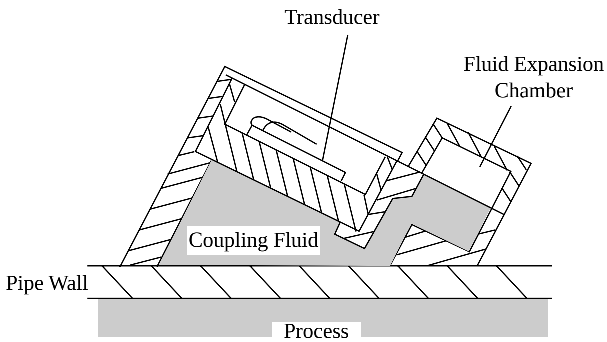


FIG. 2.26f
Liquid-filled ultrasonic coupling assembly.

DOPPLER FLOWMETERS

In 1842, Christian Doppler discovered that the wavelength of sound received by a stationary observer from a source that is moving toward the observer appears to be shorter, and the wavelength received when the source is moving away from the observer appears to be longer. The transmitter of a Doppler flowmeter projects an ultrasonic beam at a frequency of about 0.5 MHz into the flowing stream and detects the reflected frequency, which is shifted in proportion to stream velocity. The difference between transmitted and reflected velocities is called the "beat frequency," and its value relates to the velocity of the reflecting surfaces (solid particles and gas bubbles) in the process stream.

As shown in Figure 2.26g, an ultrasonic wave is projected at an angle through the pipe wall into the liquid by a transmitting crystal in a transducer mounted outside the pipe. Part of the energy is reflected by bubbles or particles in the liquid and is returned through the pipe wall to a receiving crystal. If the reflectors are traveling at the fluid velocity, the frequency of the reflected wave is shifted according to the Doppler principle in proportion to the flow velocity.

Combining Snell's law and the classical Doppler equation, the flow velocity can be determined as follows if $V << C$:

$$V = \Delta f \cdot C_t/(2 \cdot f_o \cdot \cos\theta) = \Delta f \cdot K \qquad \textbf{2.26(6)}$$

Where Δf is the difference between transmitted and received frequency, f_o is the frequency of transmission, θ is the angle of the transmitter and receiver crystal with respect to the pipe axis, and C_t is the velocity of sound in the transducer. As shown in Equation 2.26(6), velocity is a linear function of Δf. Since the inside diameter of the pipe is known, volumetric flow rate can be measured using Equation 2.26(7).

$$\text{GPM} = 2.45 \cdot V \cdot (ID)^2 \qquad \textbf{2.26(7)}$$

The single-transducer design is a popular one. Both the transmitter and received crystal are contained in a single transducer assembly that mounts on the outside of the pipe. The manufacturer thus controls alignment of the crystals. This approach is shown in Figure 2.26g.

In one form of the dual-transducer design, the transmitter crystal and the receiver crystal are mounted separately, on opposite sides of the outside of the pipe. Alignment is maintained by a mounting assembly that maintains the relative positions of the transducer as shown in Figure 2.26h.

When the process stream contains large amounts of solids (is sonically highly attenuative)—and bearing in mind that the velocity of the solid particles near the wall is likely to be less than the average, and recognizing that particles near the wall would dominate the readings in a single-transducer installation (causing large errors)—it is recommended that the two-transducer approach (supplemented by range gating) be used. With this approach, the reflected ultrasonic radiation is received from a more representative portion or portions of the flow stream.

Each manufacturer provides instructions on how to mount the transducer or transducers to the pipe. The acoustic

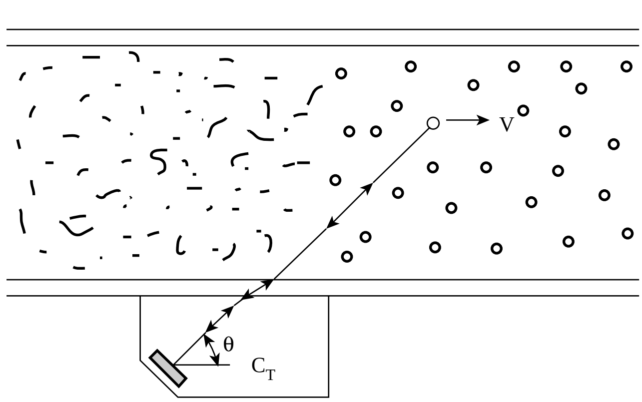


FIG. 2.26g
Doppler flowmeter principle of operation.

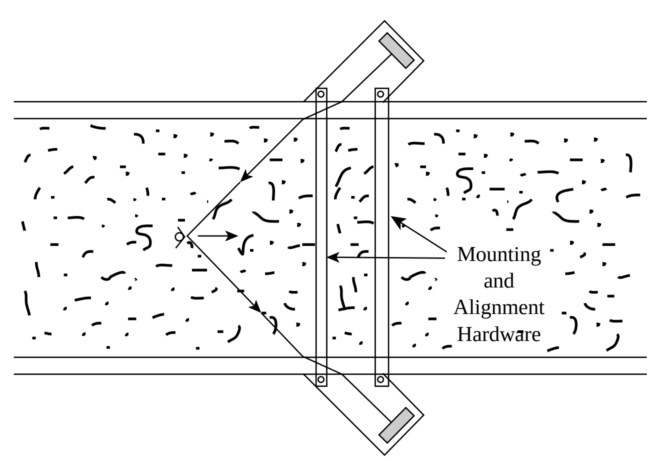


FIG. 2.26h
Two-transducer approach.

coupling to the pipe and the relative alignment of the transducers must be maintained in spite of pipe temperature changes and vibration so as to obtain acceptable performance.

Application and Performance

As with transit-time flowmeters, to properly indicate volumetric flow, the pipe must always be full. A Doppler unit will, however, indicate velocity in a partially full pipe as long as the transducer is mounted below the liquid level in the pipe.

The minimum straight pipe distance required from valves, elbow, tees, pumps, and so on is typically 10 to 20 diameters upstream and 5 diameters downstream for relatively clean fluids. This requirement can increase with process solids concentration or solids composition.

A Doppler flowmeter relies on reflectors in the flow stream to reflect the ultrasonic energy. There is a lower limit for the concentration and size of solids or bubbles in the liquid that will give reliable, accurate operation. The flow also must be fast enough to keep the solids or bubbles in suspension, typically at 6 ft/s (1.8 m/s) minimum for solids and 2.5 ft/s (0.75 m/s) for small bubbles, according to one manufacturer.

In the past few years, some manufacturers have introduced flowmeters that operate at frequencies of 1 MHz or higher. The claim for these high-frequency units is that they will operate on virtually clean liquids, because reflections will occur off the swirls and eddys in the flow stream. While this might be so, a high-frequency unit generally will not be suitable if the concentration of bubbles or particles exceeds 0.05%, because the penetration depth of the higher-frequency energy is much lower. Thus, for proper operation, a high-frequency Doppler flowmeter is limited to low-concentration applications.

On horizontal pipes, the best place to locate the transducer around the circumference should be determined on the basis of empirical testing and application experience.

The Doppler flowmeters will operate independent of pipe material if the pipe is sonically conductive. Such pipes as concrete, clay, and very porous cast iron absorb the ultrasonic energy and are not suited for Doppler-typed flowmetering. Similarly, the lining in lined pipes is not bonded well enough to allow the use of this type of clamp-on flowmeter, because even just a molecular layer of air is enough to block the transmission of the ultrasonic radiation.

The maximum operating temperatures of some ultrasonic flow transducers is about 212°F (100°C). The inaccuracy or error of the Doppler-type flowmeter is about 3% of full scale or span. The error does vary with flow velocity, pipe size, and flowmeter calibration. The error will also increase as the open flow area in the pipe changes either due to material buildup on the inside of the pipe or because the inside diameter was incorrectly measured in the first place. Repeatability is usually about 1% of full scale or full span.

DISPLAYS, RECEIVERS, AND INTELLIGENT UNITS

The electronics can be mounted either integrally with the ultrasonic flowmeter or remotely connected by cable. Remote location can be the choice for high-temperature services, although thermally isolating waveguides (Figure 2.26i) are also available. Routinely available transmitters can provide 4- to 20-mA DC analog, voltage, pulse train, or digital outputs, while the displays can provide both analog and digital indication in addition to totalization and alarming functions.

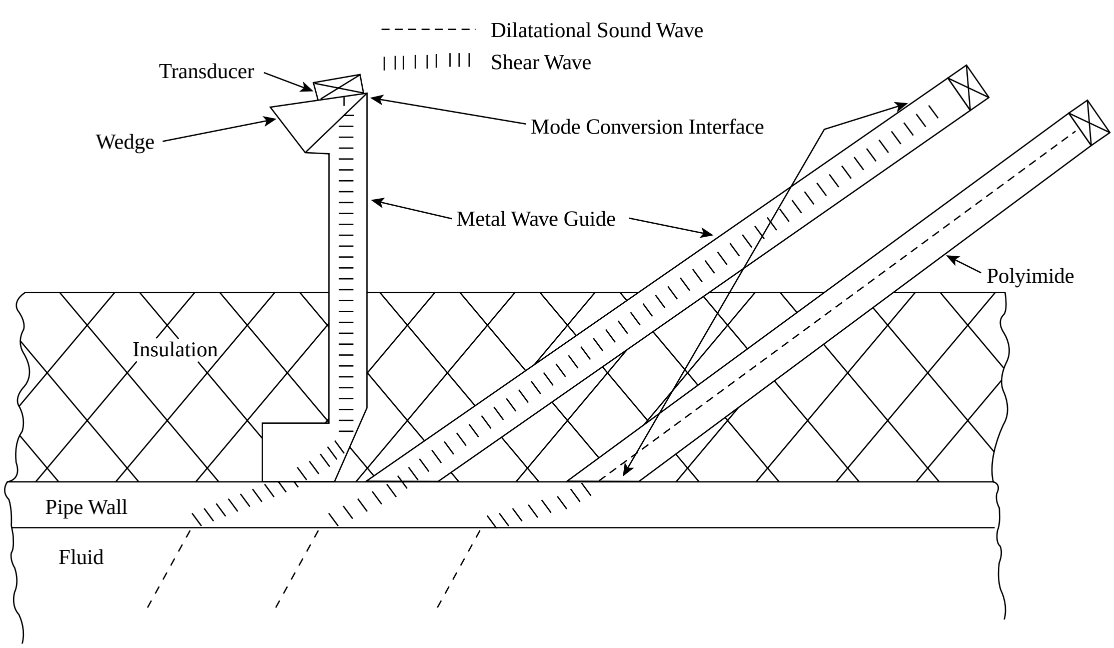


FIG. 2.26i
Three forms of thermally isolating waveguides.[2]

"Intelligent" flowmeters are capable of bidirectional flow measurement and of distinguishing true reflector movement from stationary particle or bubble vibration under no-flow conditions. One of the most promising tasks for smart ultrasonic flowmeters is to automatically evaluate the presence or absence of reflector particles or bubbles and to automatically switch from the transit-time to the Doppler reflection mode of operation and back. If and when this capability is fully developed, this "all-purpose" ultrasonic flowmeter (TransFlection®) will be able to measure the flow of both clean and dirty fluids. This capability, in combination with reduction in the unit costs, would make the ultrasonic flowmeter industry highly competitive.

ADVANTAGES OF ULTRASONIC FLOWMETERS

Ultrasonic flowmeters are members of the class of new-technology meters. Other members of this class are Coriolis, magnetic, vortex, and multivariable differential-pressure units. Ultrasonic flowmeters have some important advantages over other new-technology meters as well as over traditional-technology meters.

Ultrasonic meters have an advantage over Coriolis meters in that they do well in large-size pipes. Over 90% of Coriolis meters sold are for 2-in. pipes or smaller. Size is actually an advantage for ultrasonic meters, because there is more room for the ultrasonic beam to travel.

As compared to magnetic flowmeters, ultrasonic meters have the advantage that they can measure nonconductive fluids. Ultrasonic meters are widely used to measure liquids and gases, and they are beginning to be used for steam. Magnetic flowmeters, by contrast, are not used on gases or steams.

Ultrasonic meters measure fluids at a low flow rate better than do vortex meters. Vortex meters require a minimum Reynolds number and, therefore, a minimum velocity that might not be available at low flow rates. This is because, for a vortex meter to work effectively, the fluid has to be flowing fast enough to generate regular vortices.

As compared to traditional-technology meters such as differential-pressure (d/p) meters, ultrasonic flow detectors have the advantage of being less intrusive. The intrusiveness of d/p meters varies with the type of primary element. Clamp-on ultrasonic meters are completely nonintrusive, whereas spoolpiece meters are slightly intrusive. Insertion ultrasonic meters are somewhat more intrusive than the spoolpiece variety.

Ultrasonic flowmeters have significant advantages over turbine and positive-displacement meters. They are far less intrusive than either. Unlike both of these traditional-technology meters, ultrasonic meters do not have moving parts that are subject to wear. A great deal of competition is evolving between ultrasonic and turbine meters in their use for custody transfer of natural gas.

TABLE 2.26j
Models and Types of Ultrasonic Flowmeters by Supplier

	Type			*Operating Principle*			*Fluid*		
Company	*SP*	*CL*	*IN*	*TT*	*D*	*H*	*G*	*L*	*S*
American Sigma		x			x			x	
Automated Sonix	x	x						x	
Caldon	x	x		x				x	
Controlotron	x	x		x	x		x	x	x
Danfoss	x			x				x	
Daniel	x			x			x		
Datam Flutec			x	x				x	
D-Flow				x				x	
Durag			x	x			x		
Dynasonics		x		x	x			x	
Eastech Badger	x	x		x				x	
EES		x		x				x	
Elis Plzen	x			x				x	
EMCO		x		x				x	
Endress+Hauser		x		x				x	
Flexim		x		x				x	
Flotek UK		x		x				x	
Fluenta			x	x			x		
FMC Smith Meter	x			x			x		
Fuji Electric		x		x	x			x	
GE Panametrics		x		x		x	x	x	x
Greyline		x			x			x	
Honda		x		x				x	
Instromet	x		x	x			x		
Kaijo	x	x		x			x	x	
Kamstrup	x			x				x	
Krohne	x	x		x			x	x	x
Laaser		x			x			x	
Matelco	x	x	x	x				x	
Mesa Laboratories	x	x		x	x			x	
Micronics		x		x				x	
Monitor Labs				x			x		
Oval Corp.	x			x			x		
Polysonics		x		x	x			x	
Quality Control		x			x			x	
Rittmeyer		x	x	x				x	
Sick			x	x			x		
Siemens	x			x				x	
Solartron Mobrey		x				x		x	
Sparling	x			x				x	
Teksco USA		x			x			x	

TABLE 2.26j Continued
Models and Types of Ultrasonic Flowmeters by Supplier

	Type			Operating Principle			Fluid		
Company	*SP*	*CL*	*IN*	*TT*	*D*	*H*	*G*	*L*	*S*
Thermo MeasureTech		x			x			x	
Tokimec		x		x	x		x	x	
Tokyo Keiso	x	x		x				x	
Ultraflux		x	x	x				x	
Ultrasound Res. Ctr.		x	x	x				x	
Yokogawa		x		x				x	

SP = spoolpiece
CL = clamp-on
IN = insertion
TT = transit time
D = Doppler
H = hybrid
G = gas
L = liquid
S = steam

RECENT DEVELOPMENTS

Several important developments have occurred in this field in the past ten years. One of the most remarkable is the increased use of ultrasonic flowmeters for custody transfer of natural gas. This began in 1995, in Europe, when Groupe Europeen de Recherches GaziSres (GERG) approved the use of multi-path ultrasonic flowmeters for custody transfer of natural gas. The movement picked up steam in the United States, in 1998, when the American Gas Association (AGA) followed suit with its own approval, using independent criteria. Both approvals helped generate very rapid growth in the ultrasonic flowmeter market, and this growth continues today.

Instromet and Daniel dominate the ultrasonic flowmeter market for measuring natural gas, although FMC Energy Systems has also introduced a flowmeter for this application. Apart from the somewhat specialized area of natural gas, Panametrics and Controlotron are the top suppliers. However, Krohne is rapidly gaining ground. Thermo-Polysonics is the top supplier of Doppler flowmeters.

More than 50 ultrasonic flowmeters are available from suppliers worldwide. With so many suppliers in a fast-growth market (see Table 2.26j), consolidation seems very likely. One would expect that this consolidation will be led by the major process control equipment suppliers.

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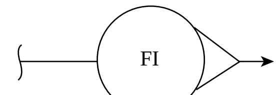
2.27 Variable-Area, Gap, and Vane Flowmeters



Flow Sheet Symbol

J. G. KOPP (1969,1982) **B. G. LIPTÁK** (1995) **T. J. BAAN** (2003)

Types

A. Rotameter (float in tapered tube)
B. Orifice/rotameter combination
C. Open-channel variable gate
D. Spring-and-vane or piston

Standard Design Pressure

A. 350 PSIG (2.4 MPa) average maximum for glass metering tubes, depending on size
Up to 720 PSIG (5 MPa) for metal tubes, special designs to 6000 PSIG (41 MPa)

Standard Design Temperature

A. Up to 400°F (204°C) for glass tubes and up to 1000°F (538°C) for some models of metal tube meters

End Connections

Female pipe thread or flanged

Fluids

Liquids, gases, and vapors

Flow Range

A. 0.01 cm^3/min to 4000 GPM (920 m^3/h) of liquid, 0.3 cm^3/min to 1300 SCFM (2210 m^3/h) of gas

Inaccuracy

A. Laboratory rotameters can be accurate to ±0.5% of actual flow; most industrial rotameters will perform within ±1 to ±2% of full scale over a 10:1 range, dual float rotameters can detect flow over a 20:1 range, and purge or bypass meters ±5 to ±10% of full range.
B and D. ±2 to ±10% of full range
C. ±7.5% of actual flow

Materials of Construction

A. Tube: Borosilicate glass, stainless steel, Hastelloy®, Monel®, Alloy 20®, PFA, Acrylic, Polysulfone, and polycarbonate. Float: *Conventional type*—brass, stainless steel, Hastelloy®, Monel®, Alloy 20®, nickel, titanium, or tantalum, and special plastic floats. Ball type—glass, stainless steel, tungsten carbide, sapphire, or tantalum. End Fittings: aluminum, brass, stainless steel, PTFE, or alloys for corrosive fluids. Packing: The generally available elastomers are used and O-rings of commercially available materials; Teflon® is also available.

Cost

A $\frac{1}{4}$-in. (6-mm) glass tube purge meter starts at $75. A $\frac{1}{4}$-in. stainless-steel meter is about $300. Transmitting rotameters in $\frac{1}{2}$-in. (13-mm) size and with 2.5% error start at about $1200 whereas, with 0.5% of rate accuracy, their costs are over $2500. A 4-in. (100-mm) transmitting rotameter with ±2.5% FS error is $3000; a 3-in. (75-mm) standard bypass rotameter is about $750, and a 3-in. stainless-steel tube standard rotameter is about $2500. A 3-in. tapered-plug variable-area meter in aluminum construction is about $1200, and the same unit in spring-and-vane design is around $800.

Partial List of Suppliers

Aalborg Instruments & Controls Inc. (www.aalborg.com) (A)
ABB Fischer & Porter (www.abb.com) (A)
Analyt-MTC GmbH (www.analyt-mtc.de) (A)
APPLIKON B.V. (www.applikon.com) (A)
Blue-White Industries (www.bluwhite.com) (A)

Brooks Instrument Div. of Emerson (www.emersonprocess.com) (A)
Cole-Parmer Instrument (www.coleparmer.com) (A, D)
Dwyer Instruments Inc. (www.dwyer-inst.com) (A, D)
ERDCO Engineering Corp. (www.erdco.com) (D)
ESKO Industries Ltd. (www.eskoindustries.com) (A)
Extech Equipment Pty. Ltd. (www.extech.com.au) (A)
Flowmetrics Inc. (www.flowmetrics.com) (A)
Gilmont Instruments Div. of Barnant Co. (www.barnant.com) (B)
Hedland Inc. (www.hedland.com) (D)
ISCO Environmental (www.isco.com) (C)
Key Instruments (www.keyinstruments.com) (A)
King Instrument Co. (www.kinginstrumentco.com) (A)
Kobold Instruments Inc. (www.koboldusa.com) (A)
Krohne America Inc. (www.krohneamerica.com) (A)
Lake Monitors Inc. (www.lakemonitors.com) (A)
Matheson Tri-Gas (www.matheson-trigas.com) (A)
McCrometer (www.mccrometer.com) (A)
McMillan Company (www.mcmillancompany.com) (A)
Meter Equipment Mfg. Inc. (www.memflow.com) (D)
Metron Technology (www.metrontech.com) (A)
Omega Engineering Inc. (www.omega.com) (A)
Osmonics (www.osmonics.com) (B)
Platon Ltd. (www.platon.co.uk) (D)
Porter Instrument Co. (www.porterinstrument.com) (A)
Spirax Sarco Inc. (www.spiraxsarco.com) (D)
Turbo Instruments Inc. (www.turbo.de) (D)
Universal Flow Monitors Inc. (www.flowmeters.com) (D)
USFilter Wallace & Tiernan Inc. (www.usfwt.com) (A)
Webster Instruments (www.webster-inst.com) (D)

The variable-area flowmeter is also a head-type flow sensor, but it does not measure the pressure drop across a fixed orifice; instead, the pressure drop is held relatively constant, and the orifice area is varied to match the flow (Figure 2.27a). In gravity-type variable-area flowmeters, increasing flow lifts the float, piston, or vane, and it is the weight of these flow elements that has to be balanced by the kinetic energy of the flowing stream. These units can operate only in a vertical position. When the lifting of the float, piston, or vane is resisted by a spring instead of gravity, the meter can be installed in any position and can be configured as a pipeline spool piece. This advantage of piping convenience has to be weighed against the fact that a spring in the process stream can be a maintenance problem and may not yield as constant a force as does gravity.

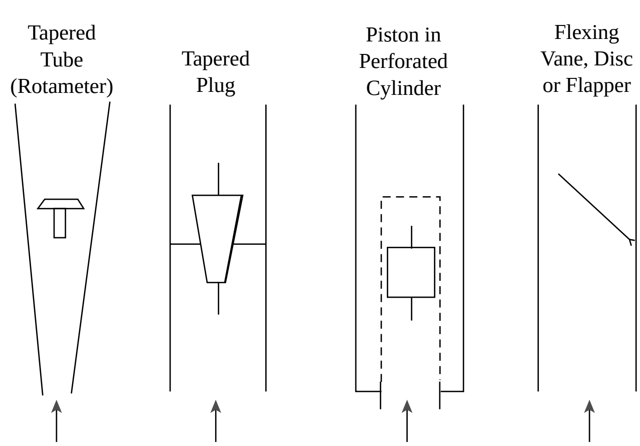


FIG. 2.27a
The area open to flow is changed by the flow itself in a variable-area flowmeter. Either gravity or spring action can be used to return the float or vane as flow drops.

All variable-area flowmeters can be provided with direct local indicators. In addition, most of them can also be furnished with pneumatic, electronic, digital, or fiber optic transmission or with microprocessors for intelligent and convenient operation. A few of the designs can also be used as self-controlled flowmeters or purge meters. In the discussion below, the different variable-area flowmeters will all be discussed, starting with the tapered tube (rotameter) designs.

ROTAMETERS

Rotameters are popular choices for low-flow measurement because of their low cost, simplicity, low pressure drop, relatively wide rangeability, and linear output. They are limited in that they can be installed only vertically, they can be used only on clean fluids, and, if glass tubes are used, they can present a safety hazard (and dirt buildup on the glass tube can limit visibility). Glass tubes are also limited in terms of their maximum pressure and temperature ratings. Their safe working pressure drops as the tube diameter increases. For a ¼-in. (6-mm) diameter tube, it is 450 PSIG (3 MPa), whereas, for a 4-in. (100-mm) diameter tube, it is only 40 PSIG (275 kPa). Because the stainless-steel float expands more with temperature than does the glass tube, the operating temperature is limited to 200°F (93°C) for a ¼-in. (6-mm) diameter tube, and this limit drops to 120°F (49°C) for a 4-in. (100-mm) diameter tube. The flow capacity of glass tube rotameters is also limited. A ¼-in. (6-mm) diameter tube will pass 0.05 to 0.5 GPM (0.19 to 1.9 l/min) water or 0.18 to 1.8 SCFM (0.3 to 3 cmph) of air. For a 3-in. (75-mm) diameter unit, the maximum water flow range is 60 to 120 GMP (225 to 450 l/min), and the maximum airflow is 200 to 500 SCFM (350 to 900 cmph). (For a detailed discussion of purge rotameters, refer to Section 2.20.)

The rotameter is a variable-area-type flowmeter. It consists of a tapered metering tube and a float that is free to move up and down within the tube. The metering tube is mounted vertically with the small end at the bottom. The fluid to be measured enters at the bottom of the tube, passes upward around the float, and flows out at the top. Figure 2.27b is a representation of a rotameter.

When there is no flow through the rotameter, the float rests at the bottom of the metering tube where the maximum diameter of the float is approximately the same as the bore of the tube. When fluid enters the metering tube, the buoyant effect of the fluid lightens the float, but it has a greater density than the fluid, and the buoyant effect is not sufficient to raise it. There is a small annular opening between the float and the tube. The pressure drop across the float increases and raises the float to increase the area between the float and tube until the upward hydraulic forces acting on it are balanced by its weight minus the buoyant force. The metering float is "floating" in the fluid stream. The float moves up and down in the tube in proportion to the fluid flow rate and the annular area between the float and the tube. It reaches a stable position in the tube when the forces are in equilibrium. With upward movement of the float toward the larger end of the tapered tube, the annular opening between the tube and the float increases. As the area increases, the pressure differential across the float decreases. The float will assume a position, in dynamic equilibrium, when the pressure differential across the float plus the buoyancy effect balances the weight of the float. Any further increase in flow rate causes the float to rise higher in the tube; a decrease in flow causes the float to drop to a lower position. Every float position corresponds to one particular flow rate, and no other, for a fluid of a given density and viscosity. It is merely necessary to provide a reading or calibration scale on the tube, and flow rate can be determined by direct observation of the position of the float in the metering tube.

Frequently, glass metering tubes are installed in metallic frames with thick, clear front shields to protect the operator from accidental spillages or leaks. There are also acrylic, polycarbonate, polysulfone, or other plastic flowmeters for lower-cost applications.

Metal metering tubes are used where glass is not satisfactory. In this case, the float position must be indirectly determined by either magnetic or electrical techniques. The use of indirect float position sensors also provides functions other than direct visual indication. Rotameters are available that transmit pneumatic, electronic, or time-pulse signals or provide recording, totalizing, or control functions. For highly corrosive applications, PTFE flowmeters with translucent PFA metering tubes are available. These meters are designed with PTFE seals and O-rings excluding elastomeric materials. Figure 2.27c illustrates a typical PTFE-PFA flowmeter.

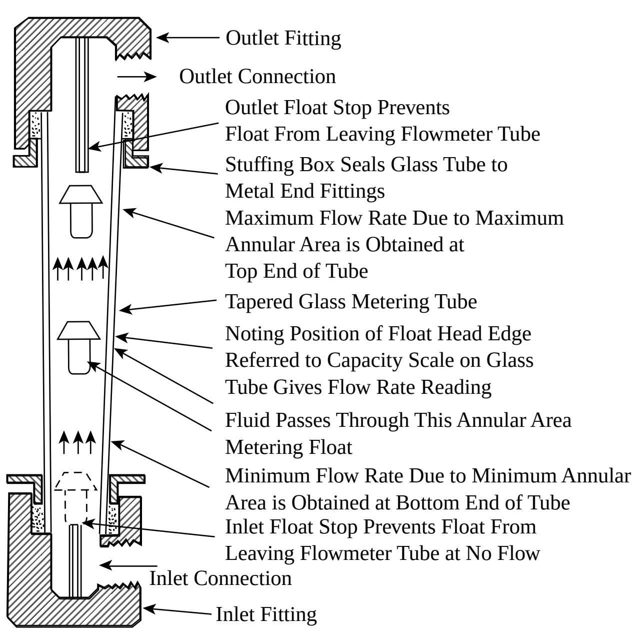


FIG. 2.27b
The rotameter.

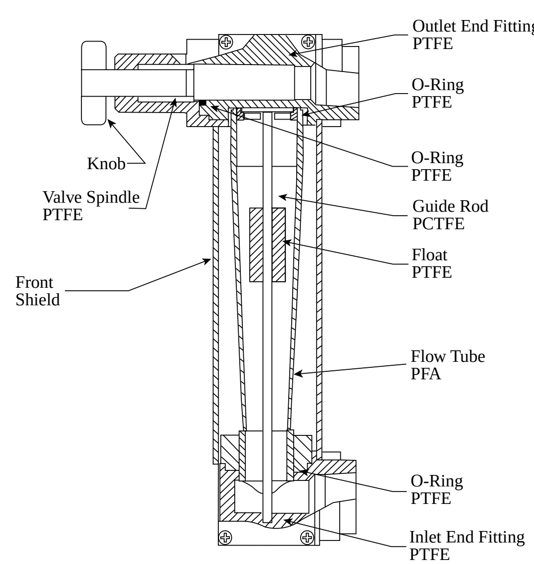


FIG. 2.27c
PTFE-PFA rotameter for highly corrosive fluids. (Courtesy of AALBORG Instruments.)

Sizing

To size a rotameter, it is customary to convert the actual flow to *standard flow*. For liquid flows, it is necessary to calculate the GPM (l/min or l/hr) water equivalent. For gases, it is necessary to determine the SCFM (l/min or l/hr) air equivalent. Capacity tables are based on these standard flows of GPM or cm^3/min of water and SCFM or cm^3/min of air at standard conditions. The tables also are based on using stainless-steel floats.

The equations necessary to calculate the water or air equivalent are provided below.

Liquids

Volume Rate

$$\text{GPM Water Equivalent} = \frac{(\text{GPM})(\rho)(2.65)}{\sqrt{(\rho_f - \rho)\rho}} \qquad \textbf{2.27(1)}$$

Weight Rate

$$\text{GPM Water Equivalent} = \frac{(\text{lbm/min})(0.318)}{\sqrt{(\rho_f - \rho)\rho}} \qquad \textbf{2.27(2)}$$

Base or Contract Volume Rate

$$\text{GPM Water Equivalent} = \frac{(\text{GPM}_b)(\rho_b)(2.65)}{\sqrt{(\rho_f - \rho)\rho}} \qquad \textbf{2.27(3)}$$

Gases or Vapors

Standard Volume Rate

$$\text{SCFM Air Equivalent} = \frac{(\text{SCFM})(\rho_{g\,std})(10.34)}{\sqrt{\rho_r(\rho_{g\,act})}} \qquad \textbf{2.27(4)}$$

Weight Rate

$$\text{SCFM Air Equivalent} = \frac{(\text{lbm/min})(10.34)}{\sqrt{\rho_r(\rho_{g\,act})}} \qquad \textbf{2.27(5)}$$

Operating or Actual Volume Rate

$$\text{SCFM Air Equivalent} = \frac{(\text{ACFM})(\rho_{g\,act})(10.34)}{\sqrt{\rho_r(\rho_{g\,act})}} \qquad \textbf{2.27(6)}$$

where

GPM = maximum flow of liquid at metering condition in units of gallons per minute
GPM_b = maximum flow of liquid at base or contract condition in units of gallons per minute
lbm/min = maximum flow of fluid at metering condition in units of pounds per minute
SCFM = maximum flow of gas referred to a base or standard condition in units of cubic feet per minute
ACFM = maximum flow of gas at operating conditions in units of cubic feet per minute
ρ = density of flowing liquid at metering conditions in units of grams per cubic centimeter
ρ_b = density of flowing liquid at base or contract conditions in units of grams per cubic centimeter
ρ_f = density of float in units of grams per cubic centimeter
$\rho_{g\,std}$ = density of gas at 14.7 PSIA and 70°F or 14.4 PSIA and 60°F in units of pounds per cubic foot
$\rho_{g\,act}$ = density of gas at metering conditions in units of pounds per cubic foot

To facilitate these computations, manufacturers offer slide rules or nomographs specifically designed for rotameter sizing.

Rotameter Characteristics

A very wide range of liquids can be handled by the rotameter. A wide choice of tube, float, end fitting, and packing or O-ring materials are available for the particular service being considered. Even liquid metals such as mercury and liquid lead can be metered. Because these metals are denser than the stainless-steel float, they are metered by an inverted rotameter. In this case, the flow is from top to bottom. When the meter is full of the liquid metal but there is no flow, the stainless-steel float is buoyed up by the heavier liquid and rests at the inlet, which is at the top. When there is flow, the flow forces the float down against the net buoyant force, and the float takes a position related to the flow rate.

The rotameter is an inexpensive flowmeter for gas flow measurement. The pressure drop across the meter is essentially constant over the full 10:1 operating range. Pressure drop is low, generally less than 1 PSI (6.89 kPa). Special designs are available for even lower pressure drops.

The position of the float in the metering tube varies in a linear relationship with flow rate. This is true over ranges up to 10:1. Percent of maximum, universal millimeter, and direct reading scales are used. Direct reading scales are convenient; however, they are valid only for the fluid for which they were designed and only at a unique set of pressure and temperature conditions. Universal millimeter scales are used in conjunction with separate calibration charts relating the elevations of the float to flow rates. The advantage of universal scales is the capability of a single flowmeter to be used for different fluids at various pressure and temperature conditions. Rotameters can directly measure flows as high as 4000 GPM (920 1/h). Even higher flow rates can be economically handled using

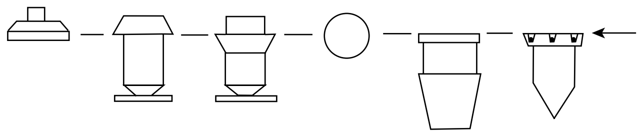


FIG. 2.27d
Variation in the shape of rotameter floats. The float on the right is provided with slots, which caused the early floats to rotate (for stabilizing and centering purposes); hence the name "rotameter."

the bypass-type rotameter. The capacity of the rotameter can be changed by changing the float. Various float configurations are available for higher capacities and generally permit a 2:1 change in capacity (Figure 2.27d). By using the same housing but changing both the metering tube and the float, a gross change in capacity is possible. These changes can be required by both a change in flow rate and a change in fluid density. For small flows in which spherical floats are employed, a downturn of better than 20:1 is achieved when two floats of different densities are installed in the same flow tube. The flow capacity of a rotameter is increased when floats have guide rods to permit the use of metering tubes with larger conical tapers.

The rotameter tends to be self-cleaning. The velocity of the flow past the float and the freedom of the float to move vertically enable the meter to clean itself of some buildup of foreign material. Liquids with fibrous materials are exceptions and should not be metered with rotameters. Generally, the size of particle, type of particle (whether fibrous or particulate), and the abrasiveness of the particle determine the suitability of the rotameter for a given service. Also, the percentage of solids by weight or by volume and the density of the solids influence the selection of the rotameter for this service.

Rotameters are relatively insensitive to viscosity variations. In the very small rotameters with ball floats, this is not the case, and the meters do respond to Reynolds number changes, which makes them sensitive to changes in both viscosity and density. However, the larger rotameters are less sensitive (Figure 2.27e). The viscosity immunity threshold can be as high as 100 cps (1 Pa · s). Meters can be operated above the viscosity limit; however, for these conditions, the meter is calibrated for discrete viscosity conditions that are to be encountered, and correction curves are furnished to adjust the indicated flow to the actual flow for the given viscosity.

The rotameter can also be used to approximate mass flow rate, given that the float responds to changes in fluid density. For a fixed volumetric flow rate, the float position in the metering tube will change with changing fluid density. The effect of fluid density changes on float position is a function of the relative densities of the float and the fluid. The closer the float density approaches the fluid density, the greater the effect of a given fluid density, and the greater the effect of a given fluid density change. It has been derived that, if the float

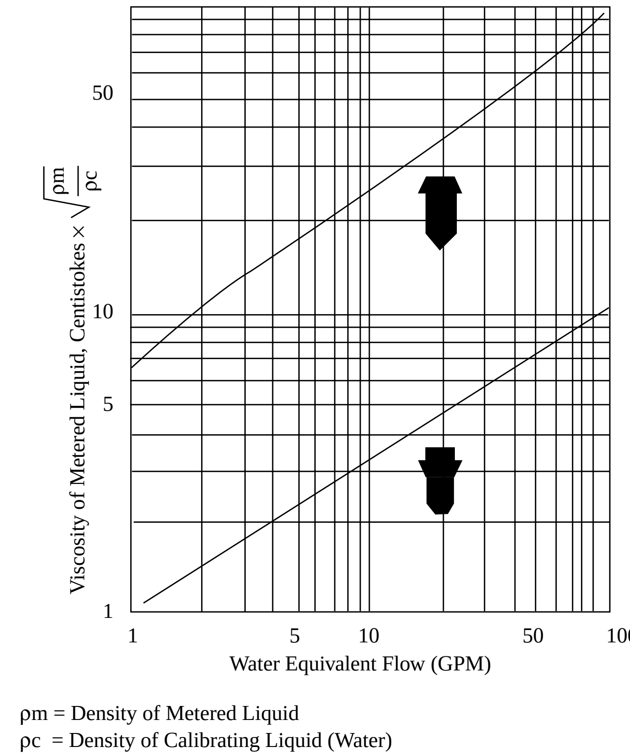


FIG. 2.27e
Viscosity limits of rotameters depend on float shape. (Courtesy of Brooks Instrument Div. of Rosemount.)

density is twice the fluid density, the compensation for fluid density change is exact, and the rotameter is a mass flowmeter. However, fluid density normally varies and, because the float density is not adjustable to follow the fluid density changes, a compromise is made. The mean fluid density is used to establish the float density. A 10% fluid density change from the reference causes only a 0.5% inaccuracy in mass flow measurement. The mass rotameter can be used only for low-viscosity fluids such as raw sugar juice, gasoline, jet fuels, and other light hydrocarbons.

Although the vast majority of rotameters operate at errors of 2 to 10% of full scale, some are available with percent-of-rate performance. Logarithmic scale meters are designed to give the same percent-of-rate accuracy at all scale positions over the 10:1 range of the meter. Accuracy statements of 0.5% of rate and 1% of rate are available. The high-accuracy type rotameter finds greatest application in laboratory testing, development, and production, where best accuracy is mandatory.

The meter is not affected by upstream piping effects. The meter can be installed with practically any configuration of piping before the meter entrance. For vacuum applications, a valve should be installed at the outlet of the rotameter to permit virtually atmospheric conditions at the inlet and inside the metering tube. This configuration will help preserve the validity of STP calibrations.

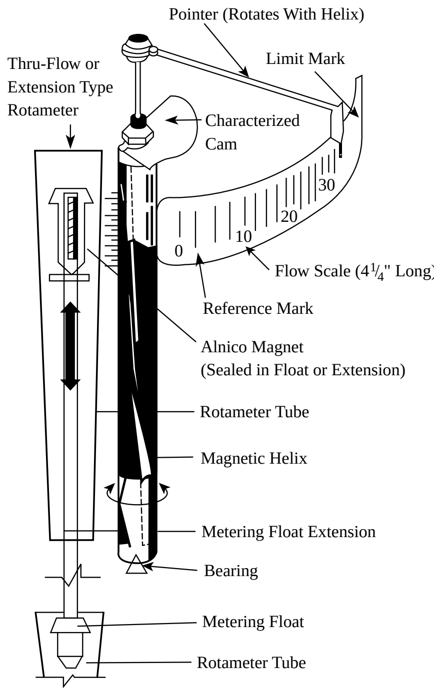


FIG. 2.27f
Magnetic coupling operates external indicator or transmitter across stainless-steel rotameter tube.

The rotameter is a highly developed flowmeter. The meters are available with an extremely broad selection of alarms, indicators, transmitters (Figure 2.27f), totalizers, controllers, and recorders. A choice of totalizers, controllers, recorders, indicators, and alarms are available locally at the flowmeter. Practically any combination of system requirements can be handled by the accessories and instruments associated with rotameters.

Rotameter Types

Figure 2.27g shows a cross-sectional view of a representative general-purpose rotameter. The meter is almost always used for flow indication only. A wide choice of materials are available for the float, packing, O-rings, and end fittings to handle the widest selection of fluids. The only fluids that cannot be handled are those that attack the glass metering tube. The meters also are limited to the pressure and temperature extremes of the glass metering tube, and by safety considerations. The accuracy of these rotameters is usually ±1 to ±2% of full scale.

Metal tube meters are used when the general-purpose meters cannot be applied. They can be used for hot (above 100°F or 38°C) and strong alkalies (above 20% concentration), fluorine, hydrofluoric acid, hot water (above 200°F or 93°C), steam, slurries, or molten metals where glass cannot be used. This classification of meters is used where the operating temperature and pressure exceed the ratings of the glass tube or, generally, where transmission of electronic or pneumatic

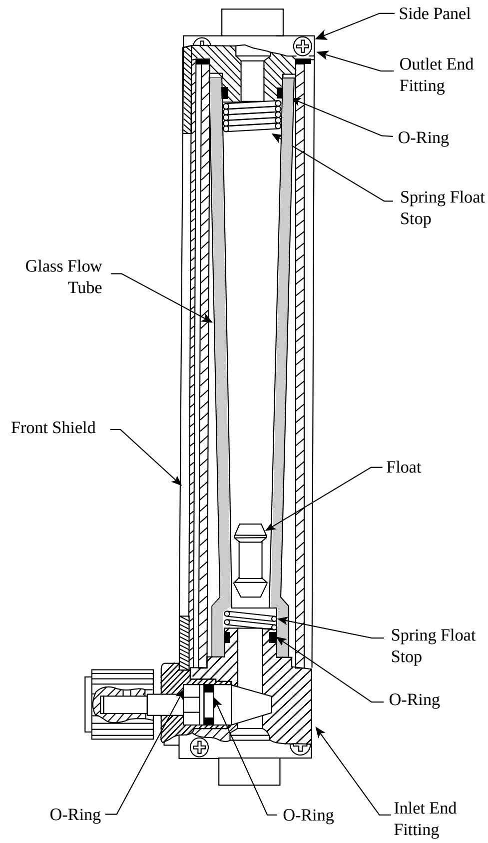


FIG. 2.27g
Typical tapered glass tube rotameter. (Courtesy of AALBORG Instruments.)

signals is needed. A typical metal tube meter is shown in Figure 2.27h.

Bypass and Pitot Rotameters

The cost of a rotameter installation can be reduced if, instead of a full pipe-size rotameter, an orifice or pitot tube is used in the main pipeline to develop a pressure drop. This, in turn, causes a related small flow that can be directed through an inexpensive bypass rotameter. Such units are illustrated in Figures 2.27i and 2.27j. The pitot-type can be used in pipe sizes of 1.5 in (38 mm) and larger, whereas the orifice bypass assemblies are available from 0.375 to 20 in. (1 to 51 cm) pipe diameters. In some designs, the bypass rotameter is provided with a range orifice that is sized to lift the rotameter float to the maximum position when the flow in the main line is at maximum. The flow measurement is linear over a 10:1 range and is accurate to about 2% of full scale with the orifice and to 5 to 10% of full scale with the pitot design. These units are usually designed for clean process streams such as water and air and are provided with easily accessible filters for periodic cleaning. The bypass rotameters are also available with isolation valves to allow for their removal and maintenance while the process is in operation.

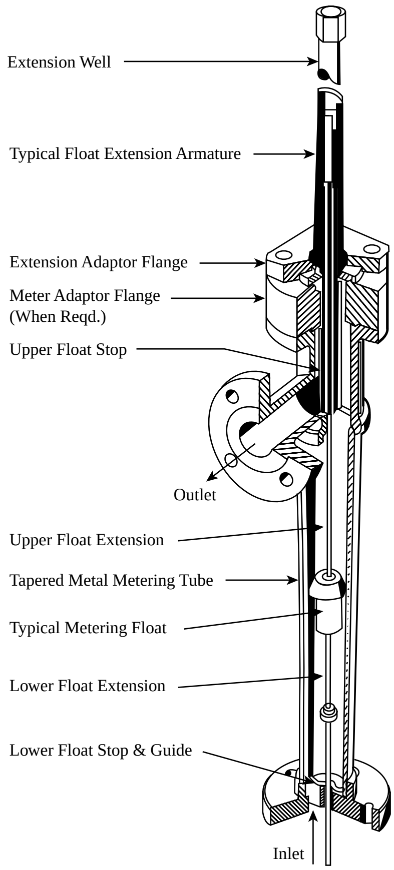


FIG. 2.27h
Metallic tube rotameter.

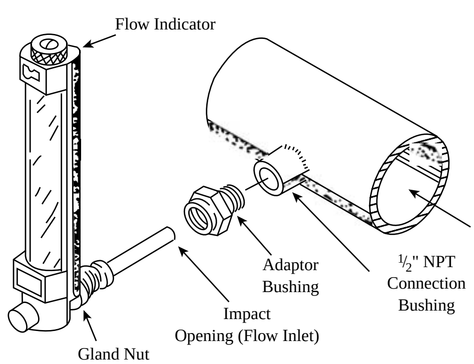


FIG. 2.27i
Pitot rotameter with bypass flow entering through impact opening (facing flow) and leaving through static port on opposite side (not shown). (Courtesy of ABB Fischer & Porter Co.)

TAPERED PLUG AND PISTON METERS

Tapered-plug variable-area flowmeters are made with metallic meter bodies and are used on higher-pressure applications where errors of 5 to 10% full scale can be tolerated. They can be gravity operated (Figure 2.27k) or spring loaded

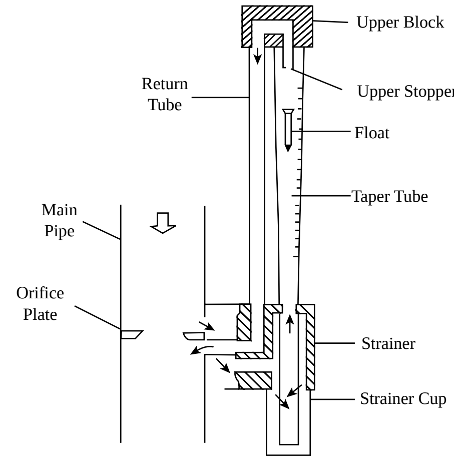


FIG. 2.27j
Bypass rotameter. (Courtesy of OSMONICS/Aquamatic.)

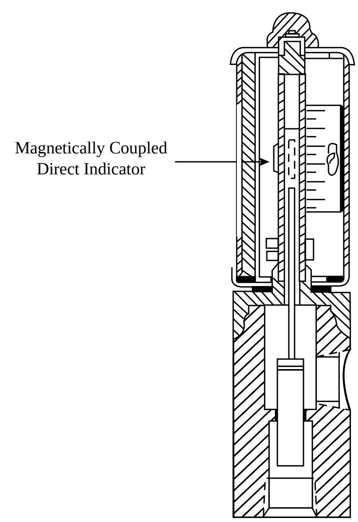


FIG. 2.27k
Tapered-plug variable-area flowmeter. (Courtesy of Brooks Instrument Div. of Rosemount.)

(Figure 2.27l) and can handle pressures exceeding 1000 PSIG (70 bars). Their sizes range from ¼ to 4 in. (6 to 100 mm), and their body materials include brass, aluminum, steel, stainless steel, and PVC. The gravity-operated units must be installed vertically, whereas the spring-loaded ones can also be horizontal. One common application is to detect the flow rate of high-pressure oil.

One type of variable-area flowmeter operates a piston in a perforated cylinder (see Figure 2.27m). This instrument is less expensive than a regular rotameter. It has been designed for clean liquid flows at rates up to 120 GPM (450 l/min) or gas flows up to 700 SCFM (20 SCMM) with pressures up to 100 PSIG (7 bars) and temperatures up to 400°F (205°C).

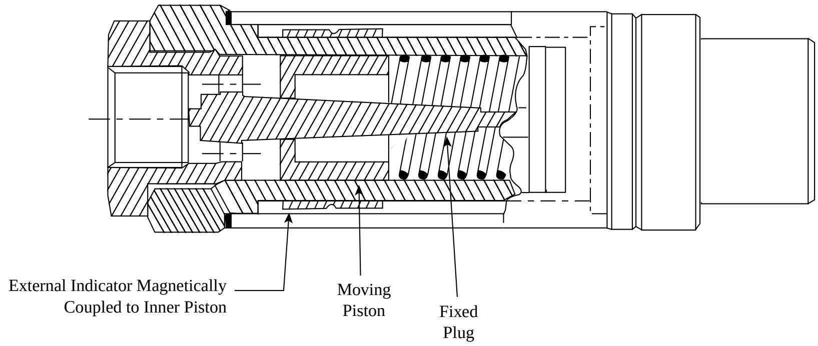


FIG. 2.27l
Tapered plug and spring-loaded piston. (Courtesy of Headland Div. of Racine Federated Inc.)

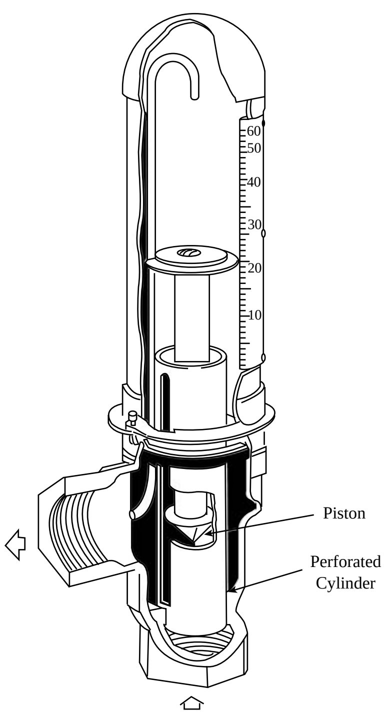


FIG. 2.27m
Piston in perforated cylinder variable-area flowmeter.

GATES AND VANES

A family of variable-area flowmeters operates by the flowing stream lifting hinged gates or forcing spring-loaded vanes to open. The variable gate is a mix of a variable-area and a flume-type flowmeter. It is used to measure wastewater or other liquids in open channels or in partially filled pipes. The meter can be inserted into 6- or 8-in. (150- or 200-mm) diameter pipes. A stainless-steel ring holds it in place, and an inflatable bladder seals the insert so that all the flow will pass through the gate opening. The pivoted gate opening is pneumatically controlled and is measured along with the upstream level to arrive at the actual flow. The same 8-in. (200-mm) insert can measure the flow from 0.25 to 500 GPM (1 to 1900 l/min).

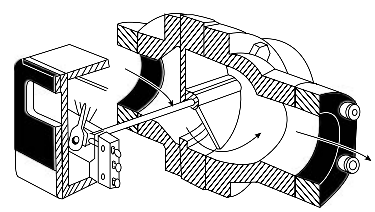


FIG. 2.27n
Rotary vane-type variable-area meter. (Courtesy of Universal Flow Monitors Inc.)

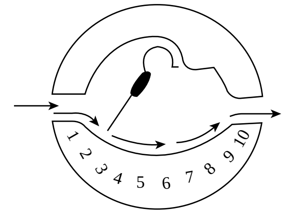


FIG. 2.27o
Magnetically coupled vane. (Courtesy of ERDCO Engineering Corp.)

Reasonable accuracy is obtained over this nearly 2000:1 flow range. Up to 10 GPM (38 l/min), the maximum error is 0.75 GPM (2.8 l/min); at higher flows, it is claimed to be 7.5% of actual reading. The meter is provided with data storage, printer, and local or remote monitoring capability.

One vane-type variable-area flowmeter resembles a butterfly valve (Figure 2.27n). The changing flow through the orifice area forces the spring-loaded vane to rotate. A shaft attached to the vane operates a pointer giving local flow rate indication. The measurement error is 2 to 5% of full scale. The meter can be used on oil, water, air, and other services and is available in ¼- to 4-in. (6- to 100-mm) sizes and in most standard materials. This variable-area flowmeter is frequently used as an indicating flow switch for safety interlock purposes.

Another vane-type variable-area flowmeter is illustrated in Figure 2.27o. This unit can also measure the flow rates of liquids, gases, and steam and is available in sizes from ½ to 12 in. (12 to 300 mm). The flow indicator is magnetically coupled to the vane, and the indication is claimed to be accurate within 2% of full scale over a 10:1 range. The flow direction through the meter can be left-to-right, right-to-left, or vertical. Operating pressures are limited to 200 PSIG (1.4 MPa). Operating temperatures are limited to 250°F (120°C) in standard and to 400°F (205°C) in units with Viton® O-rings. The housing can be aluminum, brass, copper/nickel, or stainless steel. A limitation or a possible source of error to be considered for this type of a variable area meter is posed by nearby strong electromagnetic fields that could interfere with the magnetic coupling of the indicator.

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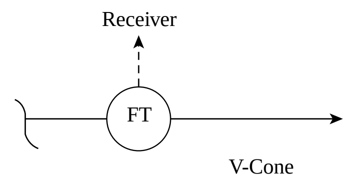
2.28 V-Cone Flowmeter

B. G. LIPTÁK (1995) **W. H. BOYES, JR.** (2003)



Flow Sheet Symbol

Applications	Liquids, gases, and steam
Sizes	From 0.5 to 72 in. (12 mm to 1.8 m) in V-cone From 0.5 to 6 in. (12 mm to 150 mm) in wafer-cone
Materials of Construction	V-cone: All type 316 stainless-steel or PVC construction with cone made out of stainless steel, PVC, or Teflon®-coated aluminum Wafer-cone: machinable in any material according to the supplier
Design Pressure	150 to 600 PSIG (10.3 to 41.4 bars) with flanged connections; higher with threaded connections
Design Temperature	From cryogenic to 700°F (371°C)
Pressure Differential	The low-range d/p cell can have a 0- to 2-in. (51-mm) H_2O range, and the high-range cell can have 0- to 30-in. (762-mm) H_2O range. If even higher rangeability is needed, a third 0- to 250-in. (6.35-m) H_2O d/p cell can be added.
Reynolds Numbers	Square root relationship is maintained down to Re = 8000.
Inaccuracy	This is a function of the calibration and accuracy of d/p cell used. With two transmitters, a 0.25% error of actual span used can be expected.
Rangeability	Over 10:1 if two transmitters are used, one for high the other for low pressure drop
Straight Pipe Run Requirements	Supplier recommends 1 to 3 diameters upstream and 1 diameter downstream.
Beta Ratios	From 0.45 to 0.85 in either version
Cost	A 0.5-in. (12-mm) flow element costs \$500. A high-quality d/p transmitter costs approximately \$1200.
Partial List of Suppliers	McCrometer (www.mccrometer.com)

In a venturi-cone (V-cone) meter, a cone is positioned in the center of a metering tube (Figure 2.28a). This cone reduces the cross-sectional area available for the process flow and, much like an orifice restriction, generates a low-pressure region downstream of the flow element. The square root of the difference between the low pressure downstream and the upstream pressure is related to the flow through the meter.

THEORY OF OPERATION

The flow or pressure drop through the V-cone meter can be calculated on liquid service using the following equations:

$$Q = 29.808 \times \frac{\beta^2 \times D^2}{\sqrt{1-\beta^4}} \times \sqrt{\Delta P} \qquad \textbf{2.28(1)}$$

$$\Delta P = \frac{Q^2 \times (1-\beta^4)}{888.517 \times \beta^4 \times D^4} \qquad \textbf{2.28(2)}$$

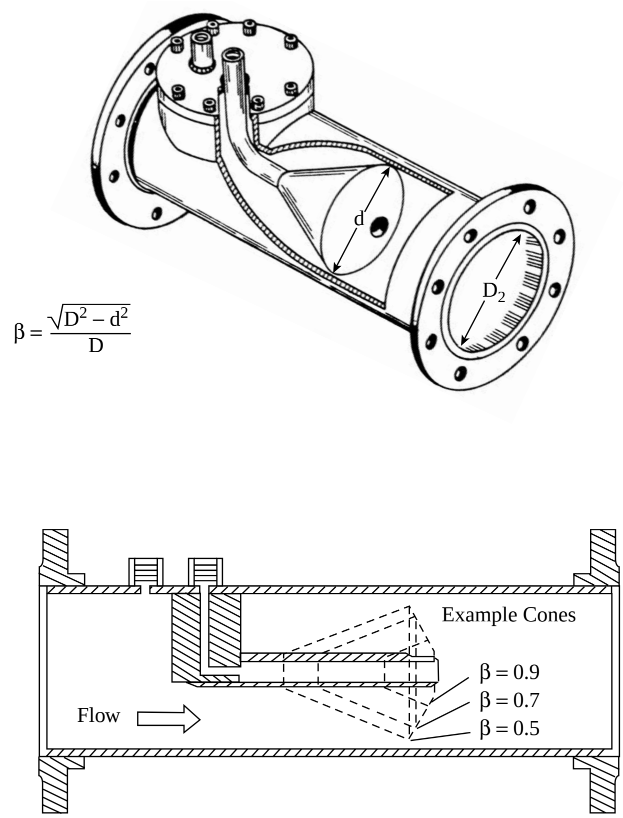


FIG. 2.28a
The V-Cone flowmeter requires less upstream straight pipe and maintains the square root relationship between flow and pressure drop at lower Reynolds numbers than does an orifice plate. (Courtesy of McCrometer Div. of Danaher Corporation.)

where

Q = water flow in GPM
D = inside diameter of the process pipe in inches
d = outside diameter of the cone in inches
ΔP = pressure drop at full flow in PSID
β = beta ratio defined as $\sqrt{D^2 - d^2/D}$

The main difference between an orifice plate and a V-cone element is that, at lower Reynolds numbers (where the velocity profile is no longer flat, as in the highly turbulent region, but starts to take on the shape of an elongated parabola, with the maximum velocity in the center of the pipe), the cone element tends to flatten the velocity profile. This is caused by the cone, which interacts with most of the flowing stream and tends to slow the flow velocity in the center while increasing it near the wall. This flow conditioning effect results in a velocity profile that is more uniform across the pipe and therefore closer to the fully developed turbulent behavior than it would be otherwise.

OPERATING FEATURES

According to the supplier, this flattening of the velocity profile results in a true square-root relationship down to a Reynolds number of 8000. Below that, the transitional and later laminar flow behavior does develop, gradually changing the square root relationship into a linear one. As with all other d/p flow elements, the V-cone is also usable in the transitional or laminar regions, but the interpretation of the pressure drop developed becomes more complex than just taking the square root. It requires the use of an accurately developed calibration curve, which can be read by the operator or can be placed into the computer's memory.

The manufacturer of the V-cone flowmeter claims very high (30:1) rangeabilities and similarly high accuracies (0.5% of actual flow), presumably over such ranges. These claims are excessive. On the other hand, we can agree that 0.1% of actual span d/p cells are available. If we use two of them (a high and a low span), we can obtain a combined range of a 100:1 in terms of pressure drop, which corresponds to 10:1 in terms of flow, and the accuracy over that range can be 1% of actual flow. Two points should be made in this connection. One is that such performance assumes that the flow element is accurately calibrated over the complete flow range. The other is that this performance can be obtained from all properly calibrated d/p flow elements, not just from the V-cone.

In addition to maintaining turbulent conditions at lower Reynolds numbers, the V-cone has the added advantage over the sharp-edged orifice of requiring less maintenance, because the flow is directly away from the cone edge. Therefore, the edge is not likely to wear. Because of the cone geometry, it also provides a sweeping action that eliminates stagnant areas and prevents gas accumulation or solids entrapment that can occur in front of sharp-edged orifices. The straight-pipe run requirements suggested by the manufacturer are substantially below those required by orifices: two diameters upstream and five downstream. This is because the cone reshapes the incoming nonuniform velocity profiles and thereby reduces the effect of upstream disturbances.

The V-cone flowmeter should be installed horizontally so that the two pressure taps are at the same elevation. This guarantees that the d/p cell will see zero pressure differential when there is no flow. If the unit is installed at a slope or vertically, it is necessary to zero out the hydrostatic head difference between taps. Any transmitting or indicating device can detect the differential pressure generated by the flow element. The manufacturer can also supply such devices, including "smart registers," that are capable of totalization and digital or analog retransmission.

A modification of the V-cone design is the wafer-cone (Figure 2.28b), which, according to the manufacturer, can be made from any material.

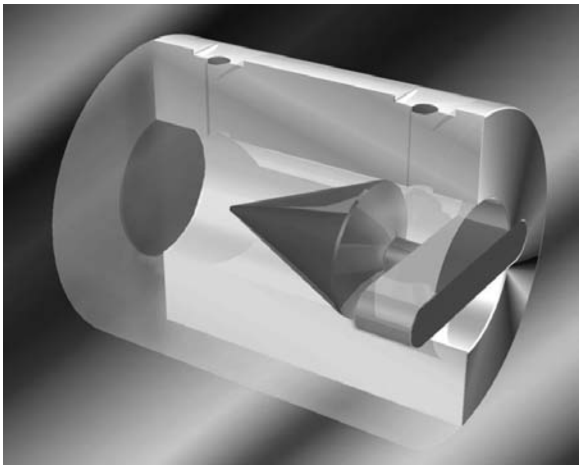


FIG. 2.28b
Wafer-Cone design modification of standard V-Cone. (Courtesy of McCrometer Div. of Danaher Corporation.)

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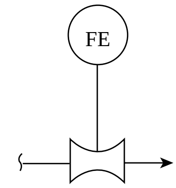
2.29 Venturi Tubes, Flow Tubes, and Flow Nozzles



Flow Sheet Symbol

W. H. Howe (1969) **L. D. Dinapoli** (1995) **J. B. Arant** (1982, 2003)

Design Types

A. Venturi tubes
B. Flow tubes
C. Flow nozzles

Design Pressure

Usually limited only by transmitter, readout device or by pipe pressure ratings

Design Temperature

Limited only by readout device, if operation is at very low or high temperature

Sizes

A. 1 in. (25 mm) up to 120 in. (3000 mm)
B. 4 in. (100 mm) up to 48 in. (1200 mm)
C. 1 in. (25 mm) up to 60 in. (1500 mm)

Fluids

Liquids, gases, and steam

Flow Range

Limited only by minimum and maximum beta (β) ratio and available pipe size range

Inaccuracy

Values given are for flow elements only; d/p cell and readout errors are additional
A. ±0.75% of rate uncalibrated to ±0.25% of rate calibrated in a flow laboratory
B. May range from ±0.5 to ±3% of rate depending on the particular design and variations in fluid operating conditions
C. ±1% of rate uncalibrated to ±0.25% calibrated

Materials of Construction

Virtually unlimited. Cast venturi tubes are usually cast iron, but fabricated venturi tubes can be made from carbon steel, stainless steel, most available alloys, and fiberglass plastic composites.

Flow nozzles are commonly made from alloy steel and stainless steel.

Pressure Recovery

Ninety percent of the pressure loss is recovered by a low-loss venturi when the beta (β) ratio is 0.3, whereas an orifice plate recovers only 12%. (The corresponding energy savings in a 24-in. [600-mm] waterline is about 20 HP.)

Reynolds Numbers

Venturi and flow tube discharge coefficients are constant at Re > 100,000. Flow nozzles are used at high pipeline velocities (100 ft/s or 30.5 m/s), usually corresponding to Re > 5 million. Critical flow venturi nozzles operate under choked conditions at sonic velocity.

Costs

Flow nozzles are less expensive than venturi or flow tubes, but cost more than orifices. ASME gas flow nozzles in aluminum for 3- to 8-in. (75- to 200-mm) lines cost from $300 to $1000. Epoxy-fiberglass nozzles for 12- to 32-in. (300- to 812-mm) lines cost from $1000 to $3000. The relative costs of Herschel venturies and flow tubes in different sizes and materials are given below:

	6-in. Stainless Steel	*8-in. Cast Iron*	*12-in. Steel*
Herschel venturi	$9000	$6000	$6500
Flow tube	$4000	$2500	$3200

Partial List of Suppliers

ABB Automation Instrumentation Division (www.abb.com/us/instrumentation) (B)
ABB Water Meters Inc. (www.jerman.com/abbmeter.html) (B)
Badger Meter Inc. (www.badgermeter.com) (A, B)
BIF Products (A, B, C)
Daniel Measurement and Control (www.danielind.com) (A, C)
Flow Technology Inc. (www.ftimeters.com) (A)
Fluidic Techniques Inc. (A)
Preso Industries (A, B)
Primary Flow Signal Inc. (A, C)
Tri-Flow Inc. (A)
West Coast Research Corp. (www.members.aol.com/wescores) (A)

Venturi tubes, flow nozzles, and flow tubes, like all differential pressure producers, are based on Bernoulli's theorem. General performance and calculations are similar to those for orifice plates. In these devices, however, there is continuous contact between the fluid flow and the surface of the primary device, in contrast to the pure line contact between the orifice plate edge and main flow. The surface finish of the devices can have some effect on the meter coefficient, although the venturi tube has a relatively constant coefficient, seldom varying more than a fraction of 1%. Modern precision manufacturing techniques allow much greater accuracy of the coefficient for venturi tubes and flow nozzles computed from dimensions, and the coefficients are only moderately less reliable than those for orifice plates. The C (meter coefficient) values for venturi tubes and flow nozzles have been well established by years of test data and are tabulated in sources such as the handbook called *Fluid Meters—Their Theory and Application.*[1] In general, this is not true of the proprietary flow tubes, and flow calibration is required to establish the actual meter coefficient. Meter coefficients for venturi tubes and flow nozzles are approximately 0.98 to 0.99 and for orifice plates average about 0.62. Therefore, almost 60% (98/62) more flow can be obtained through these elements for the same differential pressure.

THE CLASSIC VENTURI

The venturi tube, as designed by Clemens Herschel in 1887 and described in Reference 1, is shown in Figure 2.29a. It consists of

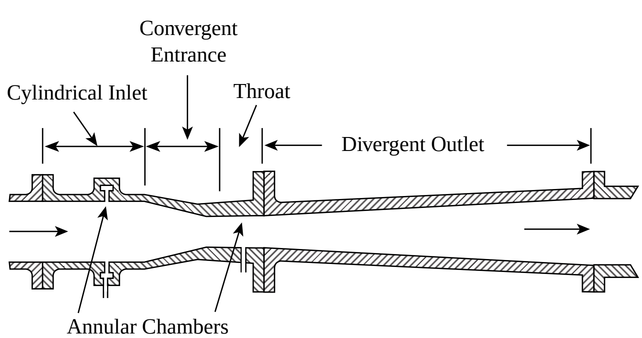


FIG. 2.29a
Classic Herschel venturi with annular pressure chambers.[1]

- A cylindrical inlet section equal to the pipe diameter
- A converging conical section in which the cross-sectional area decreases, causing the velocity to increase with a corresponding increase in the velocity head and a decrease in the pressure head
- A cylindrical throat section where the velocity is constant so the decreased pressure head can be measured
- A diverging recovery cone where the velocity decreases and almost all of the original pressure head is recovered

The unrecovered pressure head is commonly called *head loss.*

The classic venturi is always manufactured with a cast-iron body and a bronze or stainless-steel throat section. At the midpoint of the throat, six to eight pressure taps connect the throat to an annular chamber so that the throat pressure is averaged. The cross-sectional area of the chamber is 1.5 times the cross-sectional area of the taps. Because there is no movement of fluid in the annular chamber, the pressure sensed is strictly static pressure. Usually, four taps from the external surface of the venturi into the annular chamber are made. These are offset from the internal pressure taps. Throat pressure is measured through these taps. This flow meter is limited to use on clean, noncorrosive liquids and gases, because it is impossible to clean out or flush out the pressure taps if they clog up with dirt or debris. The flow coefficient for the classic venturi is 0.984, with an uncertainty tolerance of ±0.75%.

SHORT-FORM VENTURIES

In the 1950s, in an effort to reduce costs and laying length, manufacturers developed the second-generation, or *short-form*, venturi shown in Figure 2.29b. There were two major differences in this design. The internal annular chamber was replaced by a single pressure tap or, in some cases, an external pressure averaging chamber, and the recovery cone angle was increased from 7 to 21°. The short-form venturi can be manufactured from cast iron or welded from a variety of materials as compatible with a given application. The flow coefficient for the short-form venturi is 0.985, with an uncertainty tolerance of ±1.5%.

The pressure taps are located one-quarter to one-half pipe diameter upstream of the inlet cone and at the middle of the throat section. A piezometer ring is sometimes used for differential pressure measurement. This consists of several holes in the plane of the tap locations. Each set of holes is connected in an annulus ring to give an average pressure. Venturies with piezometer connections are unsuitable for use with purge systems used for slurries and dirty fluids, because the purging fluid tends to short circuit to the nearest tap holes. Piezometer connections are normally used only on very large tubes or where the most accurate average pressure is desired to compensate for variations in the hydraulic profile of the flowing fluid. Therefore, when it is necessary to meter dirty fluids and use piezometer taps, sealed sensors that mount flush with the pipe and throat inside wall should be used. These sensors function as independent measuring devices at each tap connection, yet they function together to read differential pressure only while automatically compensating for static pressure changes within the pipe. Single-pressure-tap venturies can be purged in the normal manner when used with dirty fluids. Because the venturi tube has no sudden changes in contour, no sharp corners, and no projections or stagnant areas, it is often used to measure slurries and dirty fluids that tend to build up on or clog other primary devices.

Venturies are built in several forms. These include the standard long-form or classic venturi (Figure 2.29a), a modified short form where the outlet cone is shortened (Figure 2.29b), an eccentric form (Figure 2.29c) to handle mixed phases or to minimize buildup of heavy materials, and a rectangular form (Figure 2.29d) used in ductwork. If a rectangular venturi is substantially square, it is customary to converge–diverge all four sides with angles the same as for the circular form. Where duct width differs from height, the short sides are kept parallel, with the long sides converging–diverging. A converging angle of 21° and a diverging angle of 15° give satisfactory operation. Throat length should be equal to minimum throat height or width, whichever is smaller. Tap locations are the same as for the circular form.

The angle of convergence, which may range from 19 to 23°, is the classical value established by Herschel in 1887. This angle is not particularly critical, and 21 ± 1° is commonly used. The recovery cone provides pressure recovery with its smooth flow transition. The classic long cone form is 7.5° ± 0.5° on the divergence, but up to 15° is allowed, and the sharper angle allows the short-form version to be fabricated. The 15° outlet cone sacrifices a modest amount of pressure recovery (Figure 2.29e). The venturi pressure loss of 10 to 25% is the lowest of the standard primary head measurement elements. The long-cone form develops up to 89% pressure recovery at 0.75β ratio, decreasing to 86% at 0.25β ratio. The short-cone form develops up to 85% recovery at 0.75β, decreasing to 75% at 0.25β ratio. As an example of the power savings to be obtained in an energy-short era, an added pressure recovery of 50 in. (1270 mm) H_2O differential pressure can represent a 10-HP savings in a 24-in. (610-mm) water line flowing at a velocity of 6 ft/s (1.829 m/s). For a comparison of various head-meter elements from the pressure recovery point of view, see Figure 2.29f.

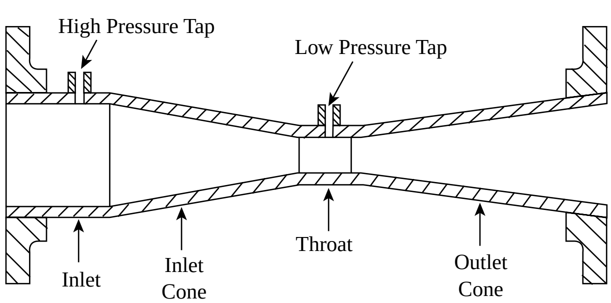


FIG. 2.29b
Short-form venturi tube.

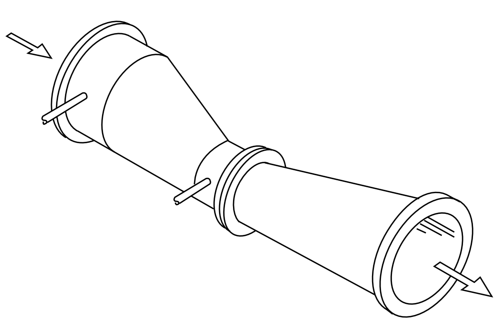


FIG. 2.29c
Eccentric venturi tube.

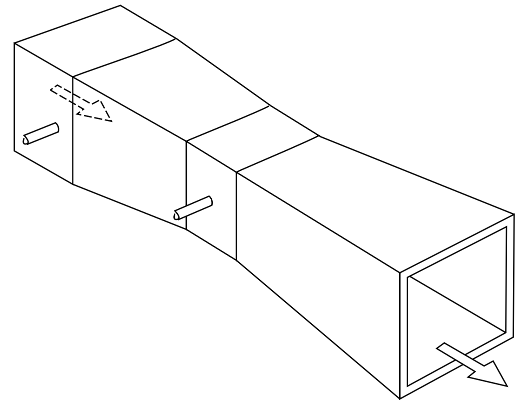


FIG. 2.29d
Rectangular venturi tube.

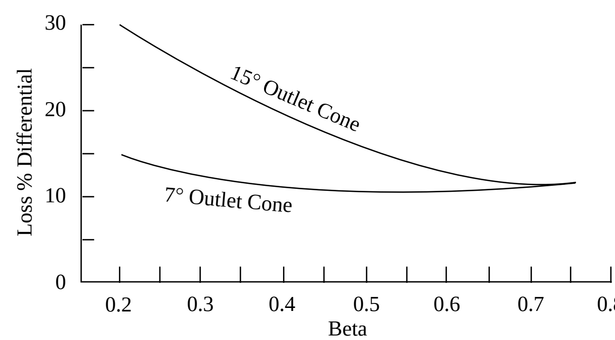


FIG. 2.29e
Venturi pressure loss.

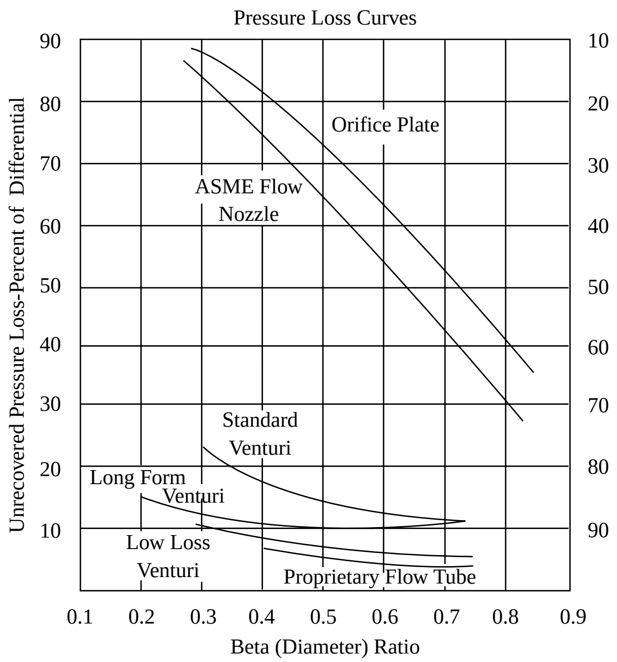


FIG. 2.29f
Pressure loss curves.

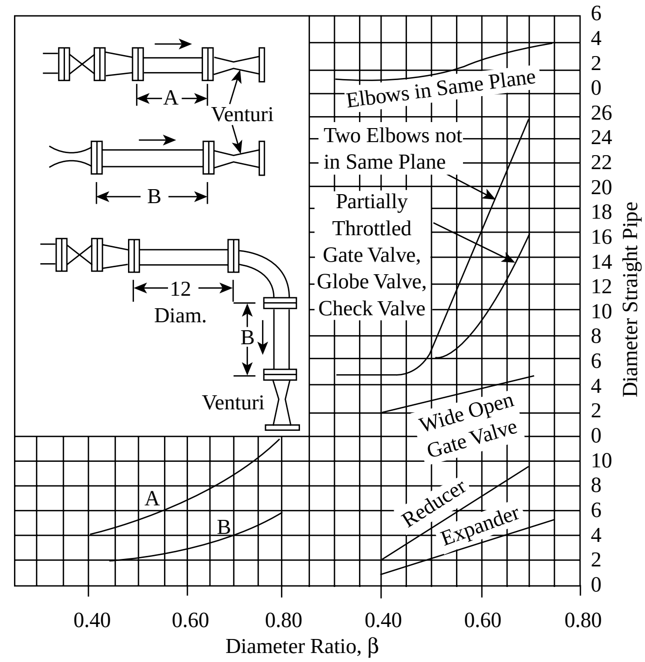


FIG. 2.29g
Venturi piping requirement.

Installation

A venturi tube may be installed in any position to suit the requirements of the application and piping. The only limitation is that, with liquids, the venturi is always full. In most cases, the valved pressure taps will follow the same installation guidelines as for orifice plates.

Upstream piping should be as long as needed to provide a proper velocity profile (Figure 2.29g). However, in most installations, shorter upstream piping is required than for orifices, nozzles, or pitot tubes, because the venturi hydraulic shape itself provides some flow conditioning. Often, the combined length of a venturi and its upstream piping is less than the overall amount of piping required for an orifice or nozzle. Figure 2.29h shows typical upstream pipe diameters required for various elements at 0.7β ratio and one elbow upstream. Straightening vanes can be used upstream to reduce the inlet pipe length.

In *Fluid Meters*,[1] the ASME recommends the use of tubular straightening vanes (19 tubes and 2 diameters long) upstream of the venturi to reduce the inlet pipe length. The vane installation should have a minimum of 2 diameters upstream and 2 diameters downstream before entering the venturi.

There is no limitation on piping configuration downstream of the venturi except that a valve should be no closer than two diameters. Valves on other devices that protrude into the flow stream should not be mounted upstream of the venturi, if possible.

Flow Calculations

The American Society of Mechanical Engineers Fluid Research Committee has adopted a general coefficient of discharge of 0.984 for the classic rough-cast entrance cone venturi tube from 4 in. (100 mm) through 32 in. (813 mm) and for β ratios between 0.3 and 0.75. For tubes with machined entrance cones, the general coefficient is 0.995. The Reynolds number must be 200,000 or greater. Approximate flow rates can be calculated from a working equation,

$$W = 353d^2\sqrt{\frac{h\rho}{1-\beta^4}} \qquad \textbf{2.29(1)}$$

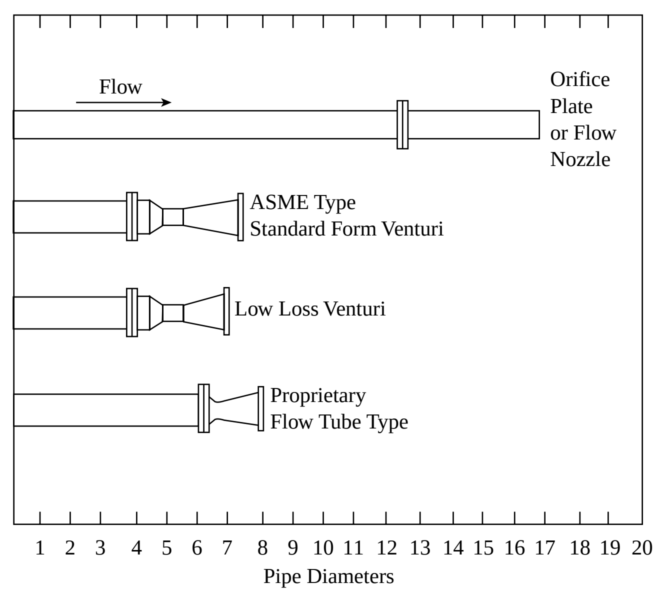


FIG. 2.29h
Typical installation piping comparison.

and, for approximate venturi tube design,

$$\beta = \frac{1}{\sqrt[4]{\dfrac{1+125,000h\rho D^4}{W^2}}} \qquad \textbf{2.29(2)}$$

For Reynolds numbers between 50,000 and 200,000, substitute 344 for 353. Below 50,000, reliable data are not available. It should be noted that, it contrast to an orifice, a decrease in Reynolds number results in a decrease of flow corresponding to a given differential pressure. Other correction factors, such as temperature coefficient of expansion, gas expansion factor, and so on, are similar to those for orifices and flow nozzles.

FLOW TUBES

There are several proprietary primary-head-type devices that have a higher ratio of pressure developed to pressure lost than a venturi tube (Figure 2.29i). They are all considerably more compact than the classical venturi tube, with its long recovery cone, although the short-from venturi can come close to some types of these tubes.

These designs are available in cast iron, can be welded from various materials, and in some cases can have insert-type units in fiberglass-reinforced plastic or metal. The flow coefficient ranges from 0.9797 for an all-static-tap "near venturi" design to 0.75 for an all-corner-tap "flow tube" design. All of these proprietary units are available in the United States except the Dall tube, which was developed in England. All of these tubes vary in contour used, tap locations, and differential pressure and pressure loss for a given flow. All have a laying length less than 4 diameters long. The shortest are the corner tap designs, with lengths equaling 2 to 2.5 diameters.

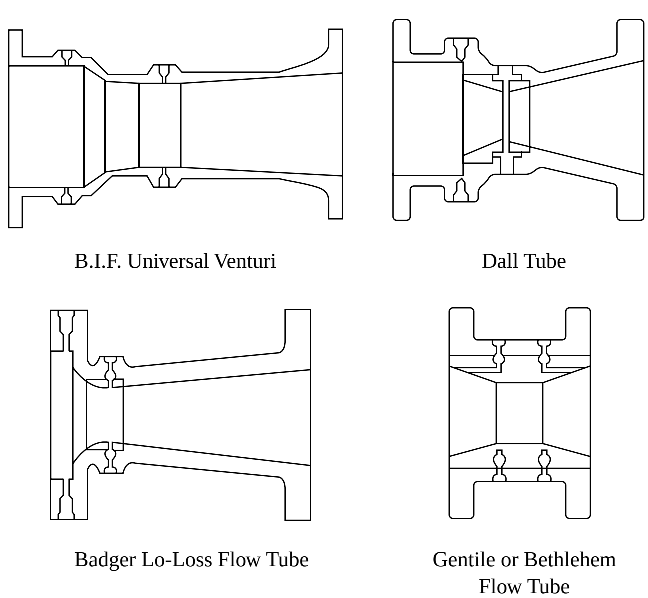


FIG. 2.29i
Proprietary flow tubes.

A *flow tube* is broadly defined by the ASME as any differential-pressure-producing primary whose design differs from the classic venturi. Flow tubes fall into three main classes, depending on the hydraulic position of the inlet and throat pressure tap. Type 1 has static pressure taps at both the inlet and outlet, Type 2 has a corner tap in the inlet and a static tap in the throat, and Type 3 has a corner tap at both the inlet and outlet.

The classic venturi had static pressure taps that provided a section in which the velocity is not changing direction and is parallel to the pipe wall. A corner tap senses pressure in a section where the velocity is changing direction and is not parallel to the pipe wall. Figure 2.29i shows examples of several flow tubes.

Type 3 flow tubes can be useful in larger sizes because of their shorter lay length, but they may also require longer upstream pipe runs for proper performance. They can be subject to coefficient change due to variations in Reynolds number, line size, and beta ratio; manufacturers can provide data on these effects.

The B.I.F. Universal Venturi is the product (Type 1) that most closely approaches the Herschel design classic venturi. The inlet cone has two *vena contracta* angles that condition the fluid as it enters the throat. This is claimed to reduce the sensitivity to upstream piping configuration and give higher accuracy. Also claimed are a stable coefficient (0.9797) that is unaffected by internal surface roughness, lower Reynolds number application (90,000), low head loss (4 to 18%), and extensive documentation including expansion factors.

Whereas flow tubes can be useful in larger sizes because of their shorter lay length, they may also require longer upstream pipe runs than the venturi for proper performance and thus lose any real advantage. They can be subject to coefficient change with viscosity and Reynolds number; manufacturers can provide data on these effects. None has the smooth contour and resistance to clogging of the venturi meter; however, some are claimed to operate satisfactorily on wastewater and sewage flow measurement.

In general, these devices are available in 4-in. (100-mm) and larger sizes up to 48 in. (1219 mm). There is little justification for their use in small-flow, small-pipe applications. In the larger sizes, their installed cost may be less than that of the venturi tube. Accuracy depends basically on the manufacturer's calibration data. Derivation of the flow coefficient by extrapolation from theory and tests on smaller sizes is much less direct than in the simple structure of the venturi tube; actual flow calibration, particularly in sizes above 24 in. (610 mm), can be difficult and expensive. Although these devices generally have a better pressure recovery than the venturi (expressed as a percentage of the differential), most flow tubes have a lower coefficient of discharge (less efficient). As a result, there is often very little difference in the actual head loss.

In selecting a primary flow element, the possible advantages of slightly lower pressure loss and shorter laying length of the flow tubes should be carefully weighed against the metering accuracy and established flow data available on the Herschel-form venturi. The ASME recommends that, if a proprietary flow tube is used, it should be calibrated with the piping section in which it is to be used and over the full range of flows to which it will be subjected. The only possible exception to this is the Universal Venturi, and it must be carefully evaluated. The background of extensive tests under a wide range of conditions that support orifice meters does not exist for these proprietary devices.

FLOW NOZZLES

There are two types of flow nozzles. The 1932 ISA nozzle is a European design that has not seen use in the United States. A special variation known as a *venturi nozzle* is a hybrid combination of a 1932 ISA nozzle inlet profile combined with the divergent cone of a venturi tube. The common nozzle used in the United States is the so-called *long-radius* or ASME flow nozzle. This nozzle comes in two versions, known as *low-beta-ratio* and *high-beta-ratio* designs. This flow nozzle, shown in Figure 2.29j, is a metering primary whose shape consists of a quarter ellipse convergence section and a cylindrical throat section. In the United States, the nozzle generally used is the long-radius ASME flow nozzle. The ASME Fluid Meters Research Committee has investigated various configurations and has developed the geometry for these nozzles based on the required beta ratio for the application. High-beta nozzles are recommended for diameter ratios between 0.45 and 0.80. Low-beta nozzles are recommended for diameter ratios between 0.20 and 0.50. For beta values between 0.25 and 0.5, either design may be used.

The difference between the two nozzles is basically a flattening of the ellipse in the high-beta-ratio version. The power test code, PTC-6, requires that the low-beta-ratio version be used in their test section for turbine acceptance.

Both types of nozzles may be either welded in the pipeline or provided with a holding ring for mounting between flanges. The latter design, shown in Figure 2.29k, is preferred when frequent inspection of the nozzle is required.

Nozzles may be manufactured from any material that can be machined; typically, they are fabricated from aluminum, fiberglass, stainless steel, or chrome-moly steel. Modern manufacturing methods and fluid contact surface finishes on the order of 6 to 10 μin result in more predictable nozzle coefficients and highly repeatable data. The standard surface finish is 16 RMS. Flow nozzle inaccuracy of ±1% is standard with ±0.25% flow calibrated. The standard coefficient, as published in Reference 1, is 0.9962 with correction factors for beta ratio and throat Reynolds number. ASME gives an uncertainty of ±–2% for nozzles having a beta ratio between 0.2 and 0.8 and throat Reynolds numbers between 1×10^5 and 2.5×10^6.

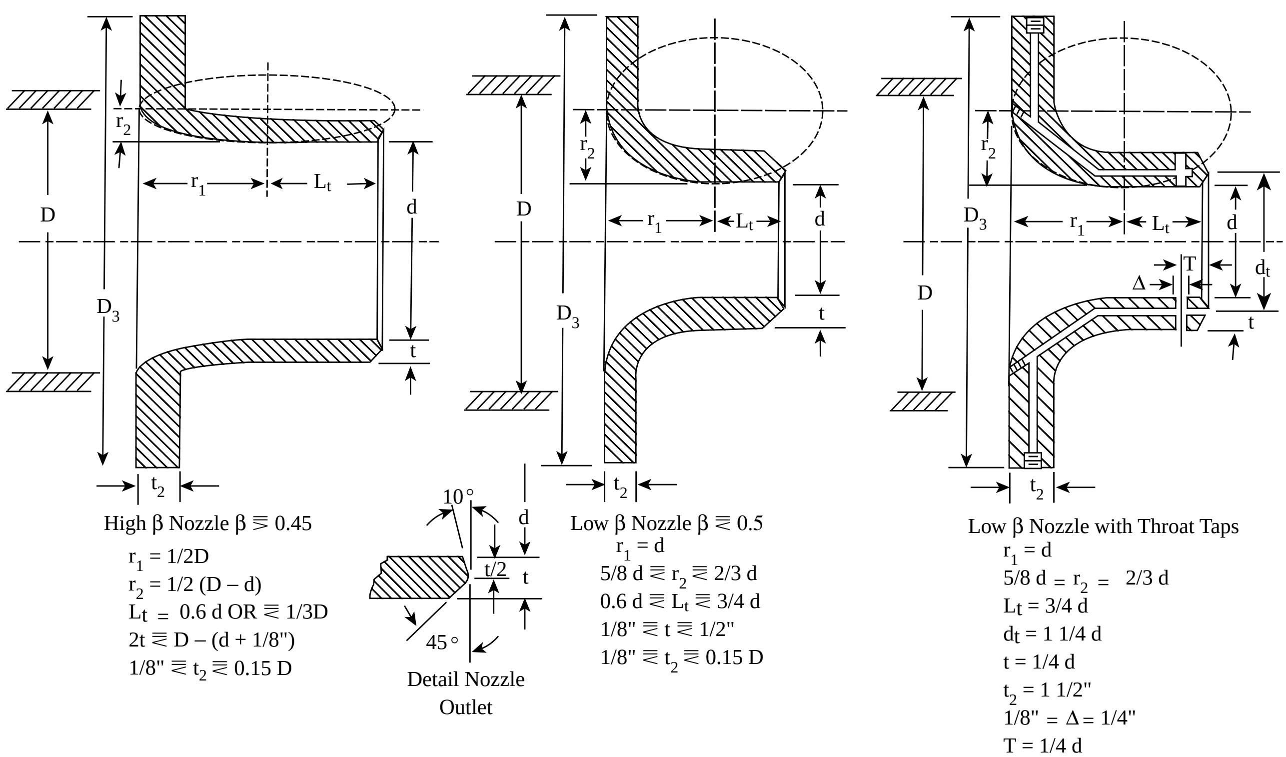


FIG. 2.29j
ASME nozzle construction.

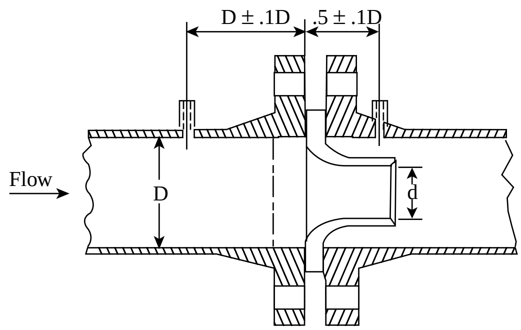


FIG. 2.29k
Typical nozzle installation.

Most ASME nozzles are calibrated as meter sections 20 pipe diameters long. As with venturi tubes, the uncertainty of calibrated units depends on the uncertainty of the hydraulic laboratory. Generally, one could expect ±0.25% uncertainty on the calibration.

The outlet or discharge side of the nozzle is normally beveled and is one of the more critical points of manufacture. Where the 10° back angle meets the throat bore, the edge must be sharp. Particular care must be taken to avoid taper and out-of-roundness of the throat.

Flow nozzles are made in various configurations. The most common is the flange type (Figure 2.29k), but others are the holding-ring type, the weld-in type, and the throat-tap type. Differential pressure measurement taps are commonly located one pipe diameter upstream and one-half pipe diameter downstream from the inlet face (U.S. practice), except for the throat-tap type, which has a special downstream construction. The PTC-6 nozzle uses throat taps to sense the low pressure and standard pipe wall taps for the high pressure.

Application Considerations

Tap installation precautions are the same as for orifice plates. The preferred installation position for flow nozzles is horizontal, but they can be installed in any position. However, a vertical downflow position is preferred for wet steam or for gases and liquids with suspended solids. In general, upstream and downstream piping requirements are similar to those required for orifices. Because of the width, nozzles installed between flanges are difficult to remove. Common practice is to provide a flange in the downstream piping to allow the nozzle to be removed as part of a spool section for inspection at regular intervals. Sometimes, inspection openings are placed just upstream of the nozzle so that frequent inspections can be made without removing the nozzle from service.

Flow nozzles are particularly suited for measurement of steam flow and other high-velocity fluids, fluids with some solids, wet gases, and similar materials. Because the exact contour is not critical, the flow nozzle can be expected to retain good calibration for a long time under erosion or other hostile conditions. Because of its streamlined contour, it tends to sweep solids or moisture through the throat and is far superior to orifice plates in these services. Because tap geometry and contour is critical to maintaining calibration, it is not recommended to use flow nozzles on slurries or dirty fluids.

A flow nozzle will pass about 60% more flow than an orifice plate of the same diameter and differential pressure. It also has the advantage of operating acceptably over a wide beta ratio range of 0.2 to 0.8. For the same flow and differential pressure, the flow nozzle has a similar but slightly lower pressure loss than an orifice plate. This becomes apparent when it is recognized that the area of the throat and the velocity in the throat of a flow nozzle must be approximately the same as the area of flow and velocity at the *vena contracta* following an orifice so as to develop the same differential pressure from the same flow. The slightly lower pressure loss of the flow nozzle is due to its streamlined entrance.

On the other hand, because the ASME flow nozzle does not utilize a recovery cone, the permanent head loss can still be as much as 40% of the differential pressure (Figure 2.29f). In an effort to reduce these losses, particularly in applications for PTC-6 testing of turbines, a recovery cone may be added. In this design, the permanent head losses can be substantially reduced. The actual amount of reduction should be determined through testing.

Although nozzles should be used at Reynolds numbers of 50,000 or above, data are available for Re down to 6000, so it is possible to use nozzles with more viscous fluids. Still, work published by the ASME Fluid Research Committee suggests that the most stable flow coefficients are seen at *throat Reynolds number* of 1×10^6. For throat Reynolds numbers below 1×10^5, the shift in flow coefficient can be as high as 6%.

Flow nozzles have very high coefficients of discharge, typically 0.99 or greater. Using a typical value of 0.993, approximate flow rates can be calculated from a working equation,

$$W = 358d^2\sqrt{\frac{h\rho}{1-\beta^4}} \qquad \textbf{2.29(3)}$$

and, for approximate flow nozzle design,

$$\beta = \frac{1}{\sqrt[4]{1+\dfrac{128,000h\rho D^4}{W^2}}} \qquad \textbf{2.29(4)}$$

CRITICAL-VELOCITY VENTURI NOZZLES

One of the most accurate ways to measure gas flow is to cause "choked" flow (sonic velocity flow) through a venturi nozzle. Critical-velocity venturi nozzles are also used as secondary flow standards in calibrating other flowmeters. The nozzle can be the ASME long-radius, elliptical inlet, wall-tap nozzle; the ISA 1932 nozzle; or the ASME throat-tap nozzle used in steam turbine testing.

One of the highest rangeability and most accurate gas flowmeters has been devised by combining the sonic venturi nozzles with the digital control valve (Figure 2.1j).

ACCURACY

Operation and calibration of venturi tubes over a period of many years has resulted in extensive documentation. As a result, most manufacturers will guarantee a standard design inaccuracy of ±0.75% of actual flow. This can be reduced to ±0.25% by calibration at a recognized hydraulics laboratory. Modern manufacturing techniques have led to predictable discharge coefficients and a repeatability of ±0.2% for venturi tubes of the same size and design.

For very small (<4 in. or 100 mm) and very large (>32 in. or 813 mm) venturi tubes, and for very high (>2,000,000) or very low (<150,000) Reynolds numbers, flow calculations for venturi tubes have about a 50% greater uncertainty than a corresponding sharp-edged orifice plate. However, fluid flow calibration, particularly when made under conditions closely approximating service values, can provide a coefficient with practically the same accuracy as that of the calibration facilities.

The error contribution of the d/p-generating flow sensor is defined as the uncertainty tolerance of the flow coefficient. The inaccuracy values can range from as low as 0.25% of rate for calibrated units to 1.5% of rate for uncalibrated welded units and can be expected to hold true only for a limited range of Reynolds numbers (see Figure 2.1f) and beta ratios.

The overall performance of the total flow measurement system therefore will be the sum of the transmitter and sensor errors. This sum will hold true only over the flow range between the maximum flow and the flow rate corresponding to the minimum Reynolds number for which the sensor error is still guaranteed. This minimum Reynolds number for venturies and flow tubes is around 100,000, and for flow nozzles it is over 1,000,000. Consequently, the rangeability of these devices, if defined in terms of actual flow error, can be rather low.

DIFFERENTIAL PRESSURE MEASUREMENT

The differential pressure generated by these primary devices (venturi, flow tubes, and flow nozzles) can be measured by manometers, gauges, and electronic pressure transmitters. The accuracy of analog electronic transmitters varies from ±0.1 to ±0.5% of calibrated span. When square-root circuitry is added, there is usually a ±0.05% increase in the error. Microprocessor-based (“smart”) transmitters have an inherent accuracy of ±0.1% of calibrated span or less, regardless of whether the square-root function is used.

Overall accuracy of the entire flowmeter system is a function of the transmitter and other instruments in the loop. The most common method for determining accuracy is to root mean square (RMS) the errors to calculate the total error. Let’s look at an example with only the primary device and an electronic transmitter. Recognize that transmitter accuracy is specified as a percent of calibrated span. Thus, at 25% of span, the error will be four times the error at full scale. The venturi, flow tube, and flow nozzle accuracy is specified as a percent of rate. Thus, the sensor accuracy is the same throughout its usable range.

Assume the venturi and the electronic transmitter are both set up such that there is a 100-in. H_2O differential pressure at full scale flow. Assume that the venturi has an accuracy of 0.75% of rate, and the transmitter has an accuracy of 0.25% of calibrated span. At full-scale flow, the total RMS uncertainty will be $\sqrt{(.75)^2+(.25)^2} = 0.79\%$. At 50% flow, the total RMS uncertainty will be $\sqrt{(.75)^2+(.50)^2} = 0.90\%$. At 25% of flow, the total RMS uncertainty will be $\sqrt{(.75)^2+(.50)^2} = 1.25\%$. At 10% flow, the total RMS uncertainty will be $\sqrt{(.75)^2+(2.5)^2} = 2.61\%$. Therefore, the transmitter can contribute significantly to the total error of the system when used over a wide range, even though the primary device maintains its accuracy over that range.

Some manufacturers of smart transmitters have routines that reduce the full-scale value of the transmitter as the differential pressure signal from the primary decreases so as to increase the total accuracy. This requires that the transmitter communicate digitally to the receiver so the reduced full scale and the measured differential pressure can be transmitted to the receiver. The total error in a flow measurement is the sum of two errors: that of the sensor and that of the transmitting or readout device. The error contribution of the best d/p transmitters is about 0.1% of span. To cover a flow range of 10:1, d/p range of 100:1 needs to be covered, which requires either an extremely wide-range d/p cell or, more likely, two d/p transmitters (a high-span and a low-span one). If such a dual-transmitter configuration is used, and if the transmitters are switched as needed, the actual error contribution of the transmitter can be limited to 1% of actual flow.

CONCLUSION

The main limitation of venturi tubes is cost, both of the tube itself and often of the piping layout required for the length necessary in the larger sizes. However, the energy-cost savings attributable to venturi tubes’ higher pressure recovery and reduced pressure loss usually justifies their use in larger pipes.

Another limitation is the relatively high minimum Reynolds number required to maintain accuracy. For venturies and flow tubes, this minimum is around 100,000, whereas, for flow nozzles, it is greater than 1,000,000. Naturally, correction data are available for Reynolds numbers below these limits, but measurement performance will suffer.

Cavitation can also be a problem. At the high flow velocities (corresponding to the required high Reynolds numbers) at the *vena contracta*, the static pressure will be low. When it drops below the vapor pressure of the flowing fluid, cavitation occurs. This, if present, will destroy the throat section of the tube, as no material can stand up to cavitation. The possible ways to eliminate cavitation include relocating the meter to a point in the process where the pressure is higher and the temperature is lower, reducing the pressure drop across the sensor, and replacing the sensor with one that has less pressure recovery.

As a result of their construction, venturies, flow tubes, and flow nozzles are relatively difficult to inspect. This problem can be solved by providing an inspection port on the outlet cone near the throat section. This can be an important factor when metering dirty (erosive) gases, slurries, or corrosive fluids. On dirty services where the pressure ports are likely to plug, the pressure taps on the flow tube can be filled with chemical seals having stainless-steel diaphragms that are installed flush with the tube interior (Figure 2.29l).

The main advantages of these sensors include their relatively high accuracy, good rangeability (on high Reynolds number applications), and energy-conserving high-pressure recovery. For these reasons, in higher-velocity flows and in larger pipelines (and ducts), the venturies are still favored by many users in spite of their high costs. Their hydraulic shape also contributes to greater dimensional reliability and therefore to better flow-coefficient stability than that of the orifice-type sensors, which depend on the sharp edge of the orifice for their flow coefficient.

The accuracy of a flow sensor is defined as the uncertainty tolerance of the flow coefficient. Accuracy can be improved by calibration. Table 2.29m gives some accuracy data in percentage of actual flow as reported by various manufacturers. These values are likely to hold true only for the stated ranges of beta ratios and Reynolds numbers, and they do not include the added error of the readout device or d/p transmitter.

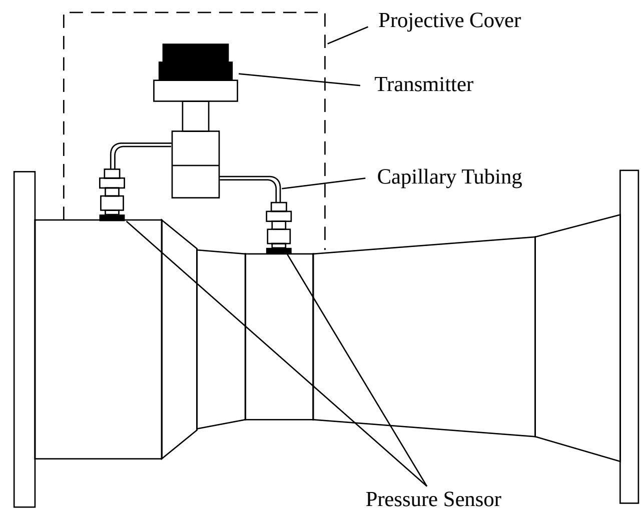


FIG. 2.29l
A variable capacitance flow transmitter can be mounted integrally to the flow tube and provided with chemical seals for protection against plugging or corrosion. (Courtesy of BIF Inc.)

TABLE 2.29m
Venturi, Flow Tube, and Flow Nozzle Inaccuracies (Errors) in Percent of Actual Flow for Various Ranges of Beta Ratios and Reynolds Numbers

Flow Sensor		*Line size, inches (1 in. = 25.4 mm)*	*Beta Ratio*	*Pipe Reynolds Number Range for Stated Accuracy*	*Inaccuracy, Percent of Actual Flow*
Herschel standard	Cast[1]	4–32	0.30–0.75	2×10^5 to 1×10^6	±0.75%
	Welded	8–48	0.40–0.70	2×10^5 to 2×10^6	±1.5%
Proprietary true venturi	Cast[2]	2–96	0.30–0.75	8×10^4 to 8×10^6	±0.5%
	Welded	1–120	0.25–0.80	8×10^4 to 8×10^6	±1.0%
Proprietary flow tube	Cast[3]	3–48	0.35–0.85	8×10^4 to 1×10^6	±1.0%
ASME flow nozzles[4]		1–48	0.20–0.80	7×10^6 to 4×10^7	±1.0%

[1] No longer manufactured because of long laying length and high cost.
[2] Badger Meter Inc.; BIF Products; Fluidic Techniques Inc.; Primary Flow Signal Inc.; Tri-Flow Inc.
[3] ABB Instrumentation; Badger Meter Inc.; BIF Products; Preso Industries.
[4] BIF Products; Daniel Measurement and Control.

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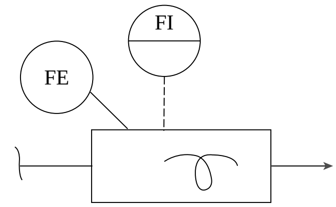
2.30 Vortex and Fluidic Flowmeters

J. G. KOPP (1969) **D. J. LOMAS** (1982) **B. G. LIPTÁK** (1995)
W. H. BOYES (2003)



Flow Sheet Symbol

Types	A. Vortex B. Fluidic-shedding Coanda effect C. Vortex precession (Swirlmeter™)
Services	A. Gas, steam, reasonably clean liquids B. Gas, reasonably clean liquids C. Gas, steam, reasonably clean liquids
Size Ranges Available	A. 0.5 to 12 in. (13 to 300 mm), also probes B. 0.5 to 4 in. (13 to 100 mm); up to 12 in. (300 mm) in bypass versions C. 0.5 to 12 in. (13 to 300 mm)
Detectable Flows	A. Water, 2 to 10,000 GPM (8 l/min to 40 m^3/hr); air, 3 to 12,000 SCFM (0.3 to 1100 SCMM); steam (D&S at 150 PSIG [10.4 bars]), 25 to 250,000 lbm/hr (11 to 113,600 kg/hr) B. Water, 0.033 to 1000 GPM (0.125 to 4000 l/min); fluids, to 80 cSt C. Water, 2 to 10,000 GPM (8 l/min to 40 m^3/hr); air, 3 to 12,000 SCFM (0.3 to 1100 SCMM); steam (D&S at 150 PSIG [10.4 bars]), 25 to 250,000 l/hr (11 to 113,600 kg/hr)
Flow Velocity Range	A and C. Liquids, 1 to 33 ft/s (0.3 to 10 m/s) Gas and steam, 20 to 262 ft/s (6 to 80 m/s)
Minimum Reynolds Numbers	A. Below Re of 8000 to 10,000, meters do not function at all; for best performance, Re should exceed 20,000 in sizes under 4 in. (100 mm) and exceed 40,000 in sizes above 4 in. B. Re = 3000; some models claim Re = 400 at specified inaccuracy, with reading down to Re = 75. C. Same as A.
Output Signals	A, B, C linear pulses or analog
Design Pressure	A. 2000 PSIG (138 bars) B. 600 PSIG (41 bars) below 2 in. (50 mm); 150 PSIG (10.3 bars) above 2 in. C. 2000 PSIG (138 bars)
Design Temperature	A. –330 to 750°F (–201 to 400°C) B. 0 to 250°F (–18 to 120°C) C. –330 to 750°F (–201 to 400°C)
Materials of Construction	A. Mostly stainless steel, some in plastic B. Cast bronze, plastic, stainless, and some specialty metals C. Mostly stainless steel, specialty alloys available
Rangeability	A. Reynolds number at maximum flow divided by minimum Re of 20,000 or more B. Reynolds number at maximum flow divided by minimum Re of 3000 (400 for some models) C. Reynolds number at maximum flow divided by minimum Re of 20,000 or more

Inaccuracy	A. 0.5 to 1% of rate for liquids, 1 to 1.5% of rate for gases and steam with pulse outputs; for analog outputs, add 0.1% of full scale B. 1 to 2% of actual flow for liquids, 1% of rate for gases claimed C. 0.5 to 1% of rate for liquids, 1 to 1.5% of rate for gases and steam with pulse outputs; for analog outputs, add 0.1% of full scale
Cost	A. Plastic and probe units cost between $250 and $1500; stainless steel units in small sizes cost about $2500; insertion types cost about $3000 B. Small versions for domestic water or heat metering cost between $50 and $125; larger versions including bypass meters cost between $300 and $1500 C. Stainless-steel units in small sizes cost about $2500, specialty materials are extra
Partial List of Suppliers	A. Aaliant Div. of Venture Measurement (www.venturemeas.com) ABB Instrumentation (www.abb.com) Asahi America (www.asahi-america.com) Bopp & Reuther (Heinrichs) Daitron (Saginomiya) Delta Controls (www.deltacontrols.com) Eastech Badger (www.eastechbadger.com) EMCO (www.emcoflow.com) Endress+Hauser Inc. (www.endress.com) The Foxboro Co. (www.foxboro.com) GF Signet (www.gfsignet.com) Hangzhou Zhenhua Meter Factory Honeywell (www.honeywell.com) J-Tec Associates (www.j-tecassociates.com) Krohne America (www.krohne.com) Metron Technology (www.metrontechnology.com) Nano-Master (www.nanomaster.com) Rosemount (now Emerson Process Measurement) (www.rosemount.com) Sparling (www.sparlinginstruments.com) Spirax Sarco Inc. (www.spiraxsarco.com) Tokyo Keiso (www.tokyokeiso.co.jp/english/index-e.htm) Vortek Yamatake (www.yamatake.co.jp) Yokogawa (www.yca.com) Yuyao Yinhuan Flowmeter Instrument Co. Zheijiang Tancy Instrument Co. B. Actaris Metering Systems (formerly Schlumberger) (www.actaris.com) Fluid Inventor AB (www.fluidinventor.se) Severn Trent Services (formerly Fusion Meter) (www.severntrentservices.com) Sontex BV (www.sontex.com) C. ABB Instrumentation (www.abb.com)

This section is devoted mainly to the vortex-shedding flowmeter and its variations, including the earlier designs of vortex-precession (swirl) meters and the recent combination designs of vortex bypass elements around orifices. Included in this category of devices are oscillating fluidic flowmeters using the Coanda effect.

THE VORTEX SHEDDING PHENOMENON

It was Tódor von Kármán who discovered that, when an obstruction (a nonstreamlined object) is placed in the path of a flowing stream, the fluid is unable to remain attached to the object on its downstream sides and will alternately separate (shed) from one side and then the other. The slow-moving fluid in the boundary layer on the bluff body becomes detached on the downstream side and rolls into eddies and vortices (Figure 2.30a). Von Kármán also noticed that the distance between the shed vortices *is constant*, regardless of flow velocity. Stated in terms of a flag fluttering in the wind, what von Kármán discovered is that the intervals between vortices (1) (or the wavelength of fluttering) is *constant* and is only a function of the diameter of the flag pole (d). Therefore, the faster the wind, the faster the vortices are formed, and the faster the flag flutters as a consequence—*but without changing its wavelength.*

Later, Strouhal determined that, as long as the Reynolds number of the flowing stream is between 20,000 and 7,000,000, the ratio between the shedder width (d) and the vortex interval (1) is 0.17. This number is called the *Strouhal number.*

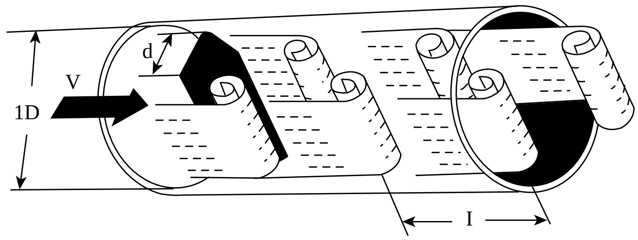


FIG. 2.30a
The distance between the Kármán vortices (l) is only a function of the width of the obstruction (d), and therefore the number of vortices per unit of time gives flow velocity (V).

Therefore, if one knows the vortex shedder width (d) and has a detector that is sensitive enough to count the vortices and determine the vortex frequency (f), one can measure the flowing velocity of any substances as

$$\text{flow velocity} = (f \times d)/(0.17) = kfd \qquad \textbf{2.30(1)}$$

In building a flowmeter based on Kármán's principle, the manufacturer usually selects an obstruction width (d) that is one-quarter of the pipe diameter (ID). As long as the obstruction is not eroded or coated, as long as the pipe Reynolds number is high enough to produce vortices, and as long as the detector is sensitive enough to detect these vortices (for gases such as hydrogen, the forces produced by the vortices are very small), the result is a flowmeter that is sensitive to flow velocity and insensitive to the nature of the flowing media (liquid, gas, steam), the density, the viscosity, the temperature, the pressure, and any other properties.

THE DETECTOR

As a vortex is shed from one side of the bluff body, the fluid velocity on that side increases, and the pressure decreases. On the opposite side, the velocity decreases, and the pressure increases, thus causing a net pressure change across the bluff body. The entire effect is then reversed as the next vortex is shed from the opposite side. Consequently, the velocity and pressure distribution adjacent to the bluff body change at the same frequency as the vortex shedding frequency changes.

Various detectors can be used to measure one of the following:

1. The oscillating flow across the face of the bluff body
2. The oscillating pressure difference across the sides of the bluff body
3. A flow through a passage drilled through the bluff body
4. The oscillating flow or pressure at the rear of the bluff body
5. The presence of free vortices in the downstream to the bluff body

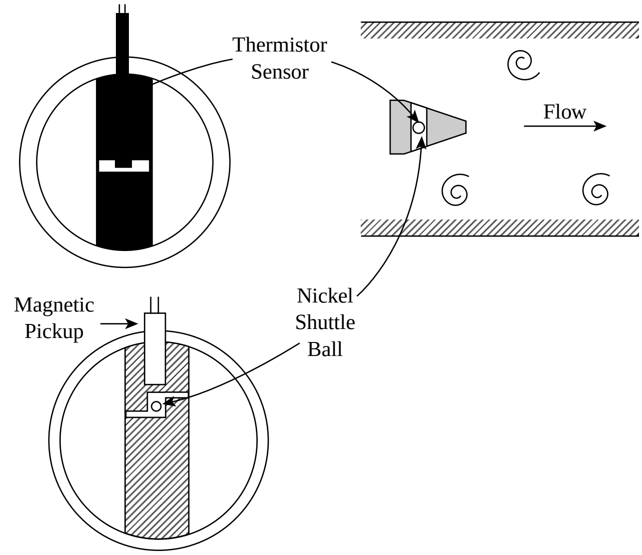


FIG. 2.30b
Shuttle-ball and shuttle-flow-type early vortex flowmeter detectors.

A flow-sensitive detector can be either a heated thermistor element or a spherical magnetic shuttle (with the movement of the shuttle measured inductively). Detectors that are sensitive to pressure use metal diaphragms or vanes. Pressure exerted on diaphragms can be converted into a variable capacitance or a variable strain on a piezoresistive, piezoelectric, or inductive sensor. Pressure exerted on vanes can similarly be converted into an electrical signal through any of the aforementioned sensors. Alternatively, the velocity components in the free vortices downstream of the bluff body can be used to modulate an ultrasonic beam diametrically traversing the meter housing. Depending on the characteristics of the sensing system, the flowmeter will be suitable for liquid, gas, or both.

The earliest detector designs were highly sensitive to plugging and required frequent maintenance (Figure 2.30b). These devices were later replaced by units that could not plug and were of solid-state design (Figure 2.30c). The majority of these designs are still marketed and are well received by users who are not concerned about quick and convenient access to, and replacement of, the detector or about the reliability and sensitivity of heat transfer or ultrasonic detectors. Still, the trend seems to be toward detectors that are modular, inexpensive, and interchangeable so they can be quickly replaced when necessary. Several vortex flowmeter detectors on today's market can be replaced easily (Figure 2.30d). In this design, the detector is a liquid-filled, double-faced diaphragm capsule with a piezoelectric crystal in the center that detects the vortex-produced pressure changes as they are transmitted through the filling liquid.

Other design modifications aim at compensating for background noise by using two detectors, one of which is exposed to vortex forces and the other is not, and using their difference as the measurement signal (Figure 2.30e). Other design

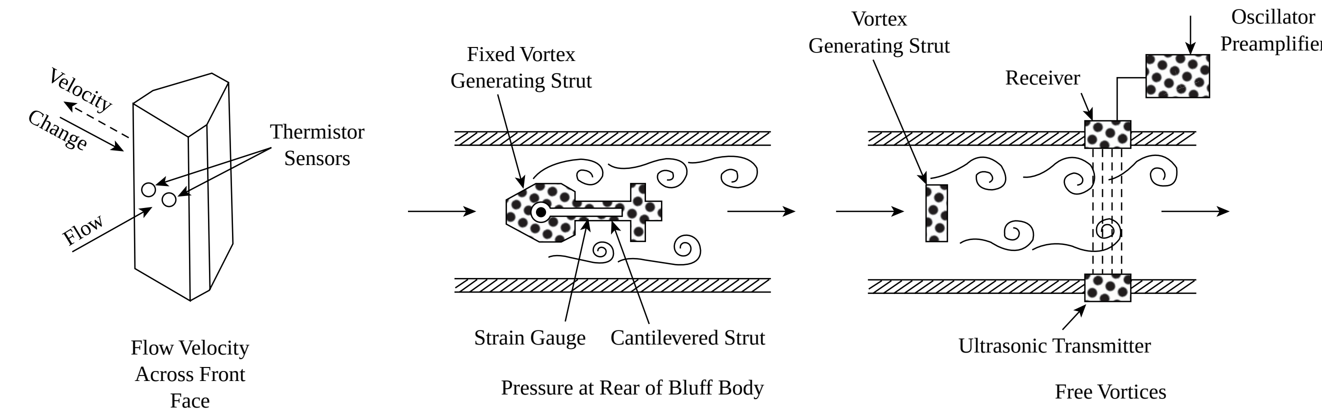


FIG. 2.30c
Solid-state vortex flowmeter designs with limited accessibility to their sensors.

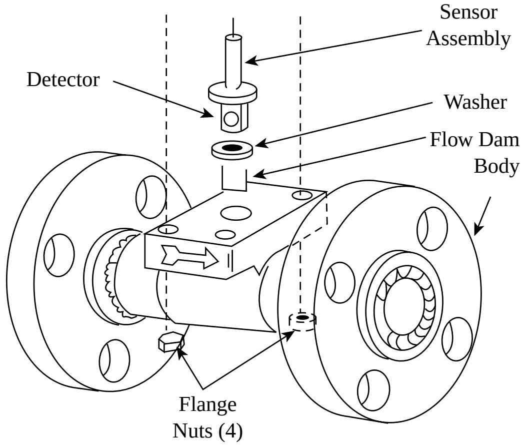


FIG. 2.30d
Piezoelectric capsule detector element is removable from flow element. (Courtesy of The Foxboro Co.)

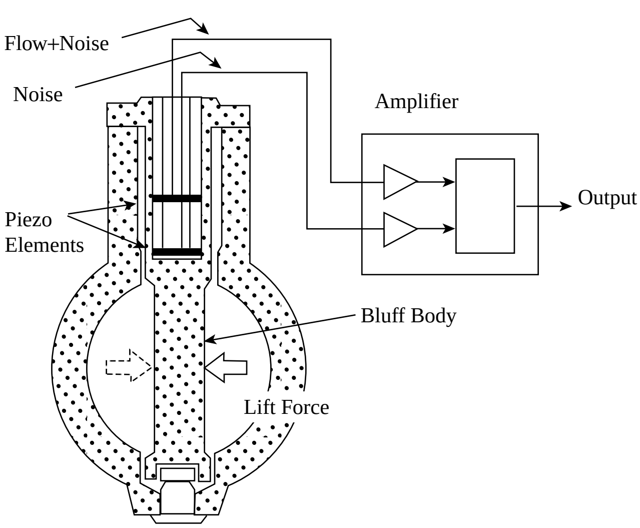


FIG. 2.30e
Dual detector serves noise compensation. (Courtesy of Johnson Yokogawa Corp. of America.)

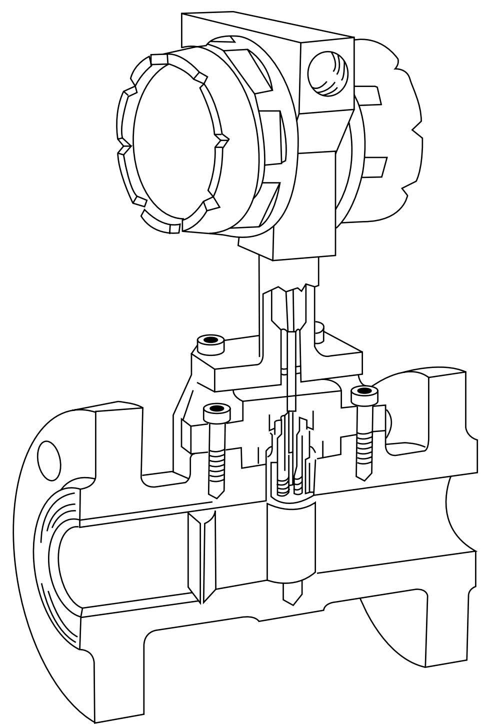


FIG. 2.30f
Separating the rugged obstruction and the detector allows the detector to be much more sensitive to the pressure waves. The increases in the forces detected allows for the use of more rugged (less sensitive and therefore less fragile) sensors. (Courtesy of EMC Co.)

modifications aim at amplifying the signal generated by low-energy vortices, such as by low-density gases. One approach is to use two detector elements (capacitance or piezoelectric) and measure the difference between their signals. This tends to amplify the detector output because, as the vortices emerge on alternate sides of the flow element, the two detectors sense the forces acting on the two different sides of the element. Still another method of amplifying the vortex forces is by physically separating the vortex shedding element and the vortex force detector (Figure 2.30f). If the vortex forces are

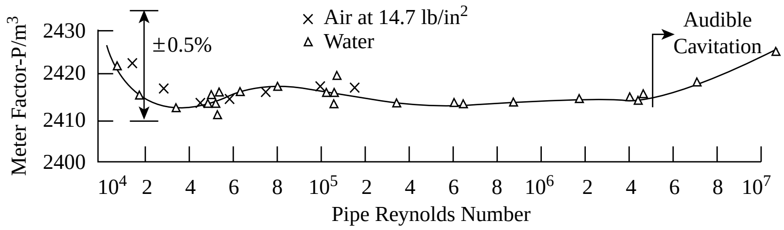


FIG. 2.30g
Typical calibration curves for a 3 in. (76 mm) vortex meter showing the close correlation between water and atmospheric air calibrations.

amplified, the force detectors can be made less sensitive and therefore more rugged and reliable.

The types of detectors in use as of this writing are listed below:

- mechanical
- thermal
- ultrasonic
- strain gauge
- capacitance
- piezoelectric

It would seem that the piezoelectric designs (particularly their dual or differential versions) dominate the market, but other designs claim superior performance under certain operating conditions. The manufacturers of the capacitance design, for example, claim superior immunity to pipe vibration effects.

The fundamental meter output is a frequency signal in all cases, which can be fed directly into digital electronic units for totalization and/or preset batching, into computers, or into data loggers. The frequency signal also can be converted into a conventional 4- to 20-mA DC analog signal for flow rate indication, recording, and control purposes. Most meters are available in either a standard form or in a design to satisfy Division 1 explosion-proof area requirements.

Features

The vortex-shedding meter provides a linear digital (or analog) output signal *without* the use of separate transmitters or converters, simplifying equipment installation. Meter accuracy is good over a potentially wide flow range, although this range depends on operating conditions. The shedding frequency is a function of the dimensions of the bluff body and, being a natural phenomenon, ensures good long-term stability of calibration and repeatability of better than ±0.15% of rate. There is no drift, because this is a frequency system.

The meter does not have any moving or wearing components, which provides improved reliability and reduced maintenance. Maintenance is further reduced by the fact that there are no valves or manifolds to cause leakage problems. The absence of manifolds and valves results in a particularly safe installation, an important consideration when the process fluid is hazardous or toxic.

If the sensor utilized is sufficiently sensitive, the same vortex-shedding meter can be used on both gas and liquid. In addition, the calibration of the meter is virtually independent of the operating conditions (viscosity, density, pressure, temperature, and so on) whether the meter is being used on gas or liquid (see Figure 2.30g).

The vortex-shedding meter also offers a low installed cost, particularly in pipe sizes below 6 in. (152 mm) diameter, which compares competitively with the installed cost of an orifice plate and differential pressure transmitter.

The limitations include meter size range. Meters below 0.5 in. (12 mm) diameter are not practical, and meters above 12 in. (30.0 mm) have limited application as a result of their high cost (compared to an orifice system) and their limited output pulse resolution. The number of pulses generated per unit volume decreases on a cube law with increasing pipe diameter. Consequently, a 24-in. (610-mm) diameter vortex-shedding meter with a typical blockage ratio of 0.3 would have a full-scale frequency output of only approximately 5 Hz at 10 ft/s (3 m/s) fluid velocity.

Selection and Sizing

As the first step in the selection process, the operating conditions (process fluid temperature, ambient temperature, line pressure, and so on) should be compared with the meter specification. The meter wetted materials (including bonding agents) and sensors should then be checked for compatibility with the process fluid with regard to both chemical attack and safety. With oxygen, for example, nonferrous materials should be used because of the reactive nature of oxygen. Applications in which there are large concentrations of solids, two-phase flow, or pulsating flow should be avoided or approached with extreme caution. The meter minimum and maximum flow rates for the given application should then be established. (See Figures 2.30h and 2.30i, and Table 2.30j.)

A typical performance curve for a vortex-shedding flowmeter is shown in Figure 2.30g. The meter minimum flow rate is established by a Reynolds number of 10,000 to 10,500, the fluid density, and a minimum acceptable shedding frequency for the electronics. The maximum flow rate is governed by the meter pressure loss (typically, two velocity heads), the onset of cavitation with liquids, and sonic velocity flow (choking) with gases. Consequently, the flow range for

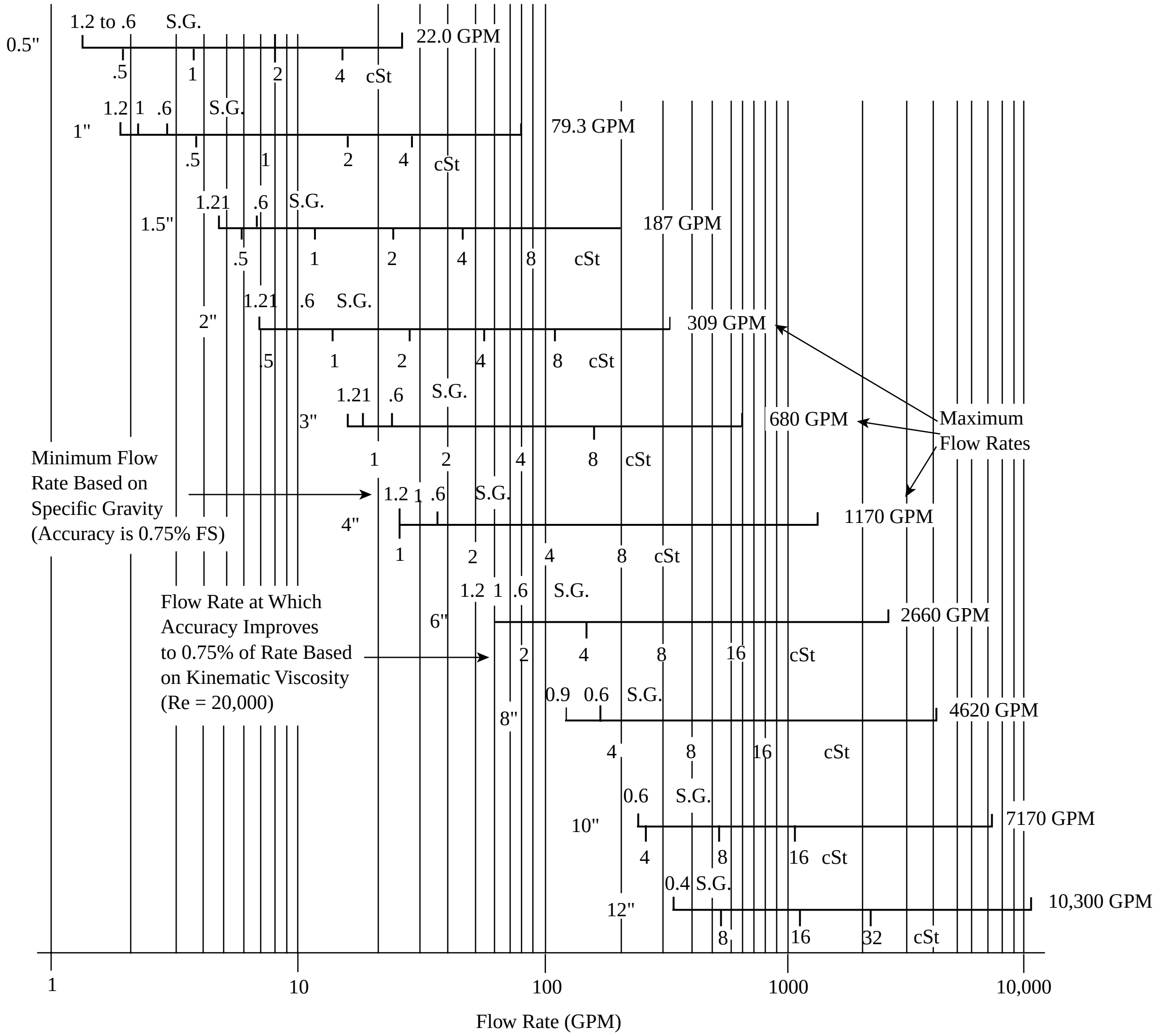


FIG. 2.30h

Sizing chart for liquid flow measurement. Note that minimum flows are limited by both specific gravity (water SG = 1) and viscosity limitations. (To convert to metric units use: 1 in. = 25.4 mm, 1 GPM = 3.78 lpm). (Courtesy of Endress+Hauser Inc.)

any application depends totally on the operating fluid viscosity, density, and vapor pressure, and the application's maximum flow rate and line pressure. On low-viscosity products such as water, gasoline, and liquid ammonia, and with an application maximum velocity of 15 ft/s (4.6 m/s), vortex-shedding meters can have a rangeability of about 20:1 with a pressure loss of approximately 4 PSIG (27.4 kPa).

The meter's good (*of-rate*) accuracy and digital linear output signal make its application over wide flow ranges a practical proposition. The rangeability declines proportionally with increases in viscosity, decreases in density, and reductions in the maximum flow velocity of the process. Vortex-shedding meters are therefore *unsuitable* for use on high-viscosity liquids.

For liquid applications, it is necessary to verify that sufficient line pressure exists to prevent cavitation in the vortex meter. The maximum pressure drop in a vortex-shedding meter is in the region of the bluff body, and there is a considerable pressure recovery by the meter outlet. Upstream line pressure requirements vary from one meter design to another, but a typical minimum acceptable upstream pressure requirement (to protect against cavitation) is given by the expression,

$$\text{Upstream pressure} \geq 1.3(\text{vapor pressure} + 2.5 \times \text{net pressure loss across the meter})$$

Cavitation conditions must be avoided at all costs, as no material can stand up to the damage caused by cavitation. One might approximate the minimum upstream pressure required to avoid cavitation (P_{min}) on the basis of the maximum velocity expected in the pipeline (V_{max}) as follows:

$$P_{min} = (1.3)P_v + (2.5)V_{max}\ {}^{2}\!/\!_{g} \qquad \textbf{2.30(2)}$$

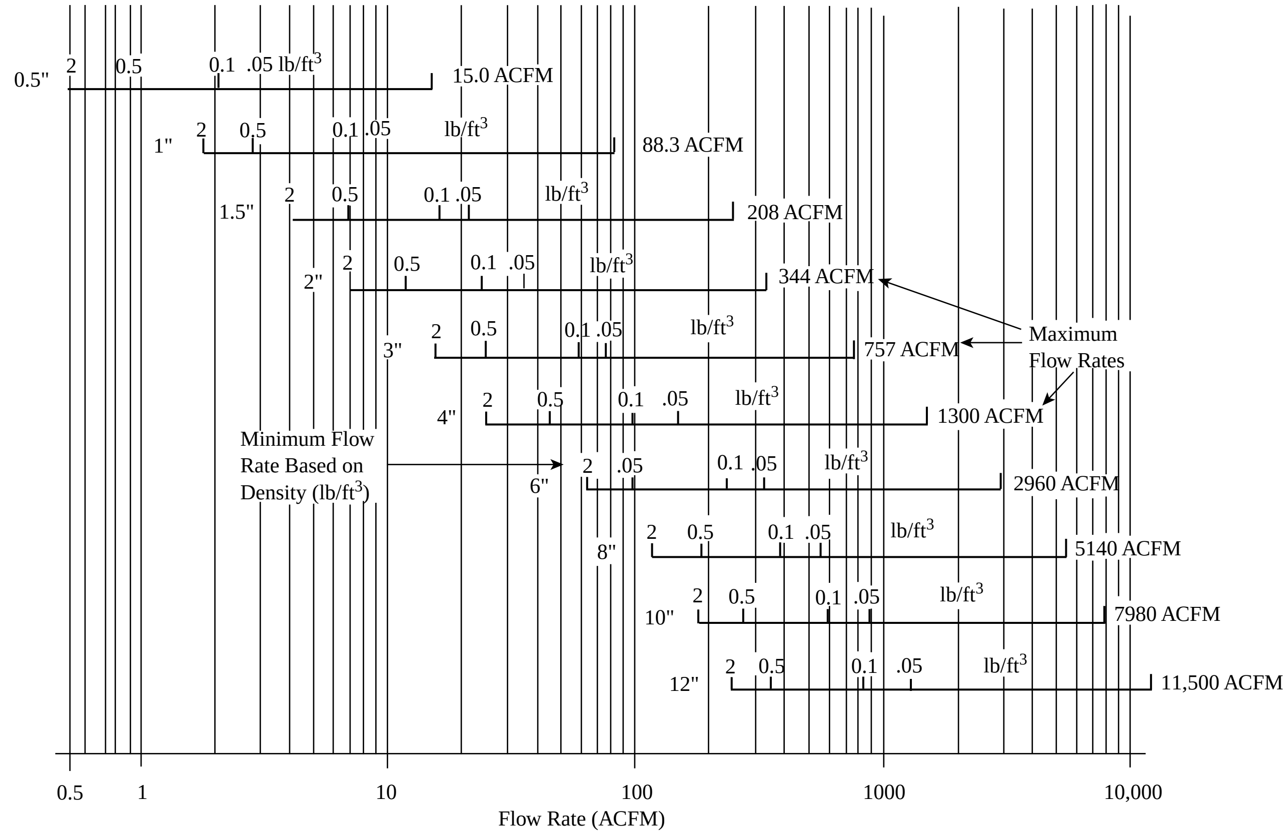


FIG. 2.30i

Sizing chart for gas and vapor flow detection: For extremely dense gases, the maximum flow may be less than shown. Gases with extremely low densities (e.g., hydrogen, helium) may not be measurable. Note that minimum flows are a function of flowing density. To convert to metric units use: 1 in. = 25.4 mm, 1 ACFM = 0.02832 ACMM, and 1 lb/ft^3 = 16 kg/m^3. (Courtesy of Endress+Hauser Inc.)

where

P_{min} = minimum required upstream pressure in feet of liquid head

P_v = vapor pressure of the flowing liquid at maximum operating temperature in feet of liquid head

V_{max} = maximum anticipated flowing velocity in feet per second

g = gravitational acceleration constant of 32.2 having the units square feet per second

Vortex-shedding flowmeters cannot survive cavitation, but they can survive episodes of *flashing* (i.e., when some of the incoming liquid stream is permanently vaporized in the flowmeter). If the liquid *gases,* the vortex-shedding flowmeter will not be mechanically damaged (although the meter output will be seriously in error).

Installation Requirements

Vortex-shedding meters require a fully developed flow profile. The length of upstream pipework necessary to ensure satisfactory approach conditions depends on the specific design of meter, the type of upstream disturbance present, and the level of accuracy required. Typical upstream and downstream pipework requirements for a variety of disturbances are given in Figure 2.30k.

Where there is a severe upstream disturbance, the resulting long, straight lengths of pipe can be reduced by fitting a radial vane or bundle-of-tubes flow-straightening element in the upstream pipework. Wherever possible, however, the meter should be installed upstream of any severe source of disturbance such as regulating control valves. The downstream straight pipe requirement is five times nominal meter diameter. The meter can be installed in any attitude (horizontal or vertical), but it is not suitable for reverse flowmetering.

Other instrument connections (pressure, temperature) all should be located downstream of the flowmeter and more than five diameters away from it. The flowmeter should be the same size as (or smaller than) the pipeline, but never larger. The unit can be insulated for cryogenic or high-temperature services and can be provided with extension bonnets. It should be installed in self-draining low points in the piping or in vertical upward flows to keep the meter flooded and to avoid air bubbles and standing liquid pools. Block and bypass valves should be provided if the meter is

TABLE 2.30j
Sizing for Steam Flow in Lb/m/Hr Units†*

Meter Size (in.)		Steam Pressure (PSIG) 10	20	30	40	50	60	80	100	150	200	250	300	350	400	500	600	700	800	900
0.5	min	10	12	13	15	16	17	19	21	25	28	31	34	36	39	40	46	51	57	63
	max	55	75	95	115	134	154	193	231	326	421	516	610	707	803	997	1197	1401	1611	1826
1	min	30	36	40	44	48	51	57	63	75	85	94	102	110	117	130	143	154	166	176
	max	322	442	560	677	792	907	1140	1360	1920	2490	3040	3600	4170	4740	5880	6440	6970	7470	7950
1.5	min	72	84	95	104	113	121	135	148	176	200	221	241	259	276	308	337	365	391	417
	max	761	1040	1320	1600	1870	2150	2690	3220	4550	5880	7190	8510	9850	11,200	13,900	15,200	16,500	17,700	18,800
2	min	119	139	156	172	186	199	223	244	290	330	365	397	427	455	507	556	601	645	686
	max	1250	1720	2180	2640	3090	3530	4420	5310	7490	9680	11,900	14,000	16,200	18,500	22,900	25,100	27,100	29,100	31,000
3	min	261	306	344	379	410	439	491	537	639	726	803	873	940	1000	1120	1220	1320	1420	1510
	max	2760	3790	4800	5800	6800	7780	9740	11,700	16,500	21,300	26,100	30,900	35,800	40,600	50,400	55,200	59,800	64,100	68,200
4	min	450	528	594	653	707	756	846	927	1100	1250	1390	1510	1620	1730	1930	2110	2280	2450	2610
	max	4760	6530	8280	10,000	11,700	13,400	16,800	20,200	28,500	38,800	45,000	53,200	61,700	70,100	86,900	95,200	103,000	110,000	118,000
6	min	1020	1200	1350	1480	1600	1720	1920	2100	2500	2840	3140	3420	3680	3920	4370	4790	5180	5550	5910
	max	10,800	14,800	18,800	22,700	26,600	30,500	38,100	45,700	64,600	83,400	102,000	121,000	140,000	159,000	197,000	216,000	234,000	251,000	267,000
8	min	1780	2080	2340	2570	2790	2980	3340	3650	4340	4930	5460	5940	6470	7120	8370	9600	10,800	12,000	13,200
	max	18,800	25,700	32,600	39,400	46,200	52,900	66,200	79,400	112,000	145,000	177,000	210,000	243,000	276,000	343,000	375,000	406,000	435,000	464,000
10	min	2750	3230	3630	3990	4320	4630	5180	5670	6740	7660	8470	9210	10,000	11,000	13,000	14,900	16,800	18,600	20,500
	max	29,100	39,900	50,600	61,200	71,700	82,100	103,000	123,000	174,000	225,000	275,000	326,000	377,000	429,000	532,000	582,000	630,000	676,000	720,000
12	min	3970	4660	5240	5760	6240	6670	7470	8180	9720	11,000	12,200	13,300	14,500	15,900	18,700	21,500	24,200	26,900	29,500
	max	42,000	57,600	73,000	88,300	103,000	118,000	148,000	178,000	251,000	324,000	397,000	470,000	544,000	618,000	767,000	840,000	909,000	975,000	1,040,000
$Temp_{sat.}$	°F	239	259	274	287	298	307	323	338	366	388	406	422	436	448	470	489	506	520	534
$Density_{sat.}$	lb/ft^3	0.061	0.083	0.106	0.128	0.150	0.171	0.214	0.257	0.363	0.469	0.574	0.679	0.787	0.894	1.11	1.33	1.56	1.79	2.03

*To convert to metric units use: 1 in. = 25.4 mm, 1 PSIG = 0.069 bars, and 1 lbm = 0.454 kg.
†Courtesy of Endress + Hauser Instruments.

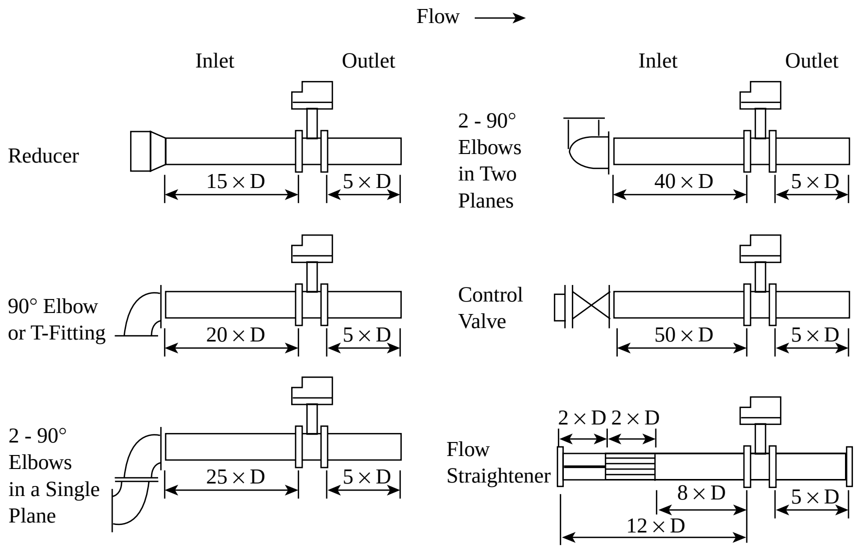


FIG. 2.30k
Straight pipe-run requirements as a function of upstream disturbance. (Courtesy of Endress+Hauser Inc.)

to be serviced while the process is in operation. There should be no excessive pipe vibration in the area where the meter is installed, and gaskets should not protrude into the pipeline.

VORTEX-PRECESSION (SWIRL) METERS

A predecessor of the vortex-shedding meter, the vortex-precession meter or Swirlmeter™, is currently manufactured by a single vendor and sold in combination with that vendor's vortex-shedding product line, sharing common sensors, electronics, and programming features.

Construction of a typical vortex-precession (swirl) meter and the operating principles are illustrated in Figure 2.30l. The fixed, swirl-inducing helical vanes at the entrance to the meter introduce a spinning or swirling motion to the fluid. After the exit of the swirl vanes, the bore of the meter contracts progressively, causing the fluid to accelerate, but with the axis of rotation still on the centerline of the meter. The swirling fluid then enters an enlarged section in the meter housing, which causes the axis of fluid rotation to change from a straight to a helical path. The resulting spiraling vortex is known as *vortex precession.* The frequency of precession is proportional to velocity and, hence, volumetric flow rate above a given Reynolds number.

The velocity of fluid in the vortex is higher than that of the surrounding fluid. Consequently, as each vortex passes the sensor, there is a change in the local fluid velocity. The frequency at which the velocity changes occur is proportional to volumetric flow rate and can be detected by piezoelectric or thermistor sensors. Currently, the only vortex-precession meter in manufacture uses piezoelectric sensors.

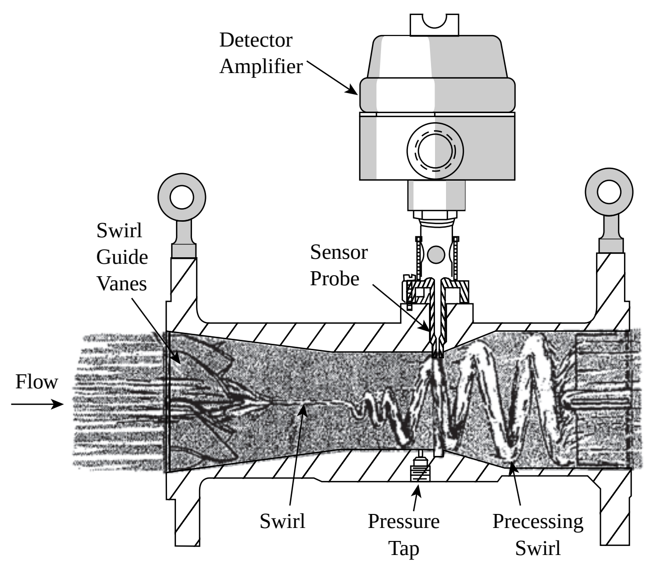


FIG. 2.30l
Construction of a typical vortex-precession (swirl) meter.

A flow straightener is fitted at the meter outlet to isolate the meter from downstream piping effects that might otherwise impair the development of the precessing vortex.

The internal components of the swirl meter required a significant amount of complex machining; thus, it is more expensive than some other meter types.

The swirl meter operates in most of the same applications as the vortex-shedding flowmeter but has the advantage that, since flow conditioning is done at the inlet and outlet of the meter body, virtually no upstream or downstream straight run is required for optimal installation. The sole supplier currently furnishes the swirl meter and the vortex-shedding meter in interchangeable "kits."

FLUIDIC (COANDA EFFECT) METERS

In fluidic meters, fluid entering the meter is entrained into a turbulent jet from its surroundings, causing a reduction in pressure. The internal geometry of the meter body causes the jet to be deflected from its central position and initially attach itself to one of the side walls. The jet curvature is sustained by the pressure differential across the jet. If a sufficient volume of fluid is then introduced into the control port on that side, it will cause the jet to switch to the opposite side wall. This is known as a *Coanda effect*. The jet can be made to oscillate by one of two methods. The simplest method is a relaxation oscillator. In this system, the two ports are connected. Fluid is sucked from the high-pressure side to the low-pressure side causing the jet to switch to the other wall. The jet thus continues to oscillate as the fluid is sucked alternately from one side to the other.

The more commonly used system is the feedback oscillator (see Figure 2.30m). The deflected jet causes a low-pressure area at the control port. At the upstream feedback passage, the pressure is higher due to a combination of the jet expansion and the stagnation pressure. Thus, a small portion of the main stream of fluid is diverted through the feedback passage to the control port. The feedback flow intersects the main flow and diverts it to the opposite side wall. The whole feedback operation is then repeated, resulting in a continuous, self-induced oscillation of the flow between the side walls of the meter body. The frequency of oscillation is linearly related to the volumetric flow rate above a minimum Reynolds number. As the main flow oscillates between the side walls, the flow in the feedback passages oscillates between zero and a maximum value. This frequency is detected by means of a sensor (either a thermistor or magnetic inductive pickup), providing a frequency output signal.

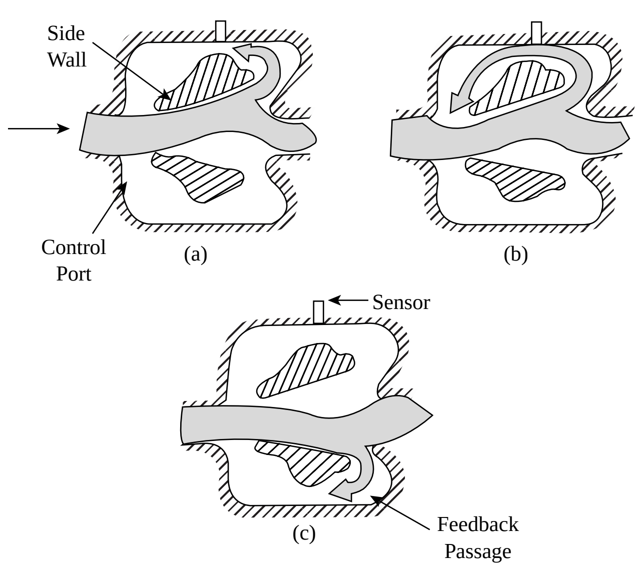


FIG. 2.30m
Diagram of the mode of operation of a feedback oscillator.

Characteristics

The principal features include a lack of moving components, fixed calibration based on the geometry of the housing, linear digital or analog output, and good rangeability. One advantage over vortex meters is that fluidic meters can operate down to a Reynolds number of 3000. The maximum flow range (dependent on size and viscosity) is 30:1. The complex housing shape largely dictates the operating pressure and maximum practical pipe diameter. In practice, a 4-in. (100-mm) diameter unit is the largest commercially available, and the operating pressure in this diameter is typically limited to 150 PSIG (1.03 MPa). Some vendors provide larger diameters up to 12 in. (300 mm) by using a bypass flow tube design. In this design, a flow restriction is placed in the tube, forcing fluid through the fluidic flowmeter mounted on top of the flow tube.

Although theoretically suitable for gaseous applications, fluidic meters have been used almost exclusively in liquid applications. Recent experimentation by several manufacturers has produced fluidic flowmeters that appear to be able to meet AGA certification requirements for household gas meters, and one manufacturer has placed a fluidic-principle gas meter in distribution for industrial and commercial natural gas metering applications.

A special, separate converter is required for the meter, which, in some instances, can incorporate a pneumatic output. As shown in Figure 2.30n, the meter factor in pulses per volume of flow passed remains within 1%, and therefore the measurement error remains well within 2% of actual flow between the Reynolds numbers of 3000 and 100,000.

CONCLUSION

The advantages of vortex-shedding flowmeters include their suitability for liquid, gas, and steam service; independence from viscosity, density, pressure, and temperature effects; low installed cost in smaller sizes; good accuracy and linearity without requiring calibration; wide rangeability; low maintenance using simple, easily accessible and interchangeable spare parts; simple installation; and direct pulse output capability.

In terms of disadvantages, they are not suitable for services that are dirty, abrasive, viscous, or mixed-flow (gas with liquid droplets, liquid with vapor bubbles), or that have low Reynolds numbers (below 20,000); the available choices in materials of construction are limited; the pulse resolution (number of pulses per gallon or liter) drops off in larger sizes; the pressure drop is high (two velocity heads); and substantial straight runs are required both upstream and downstream.

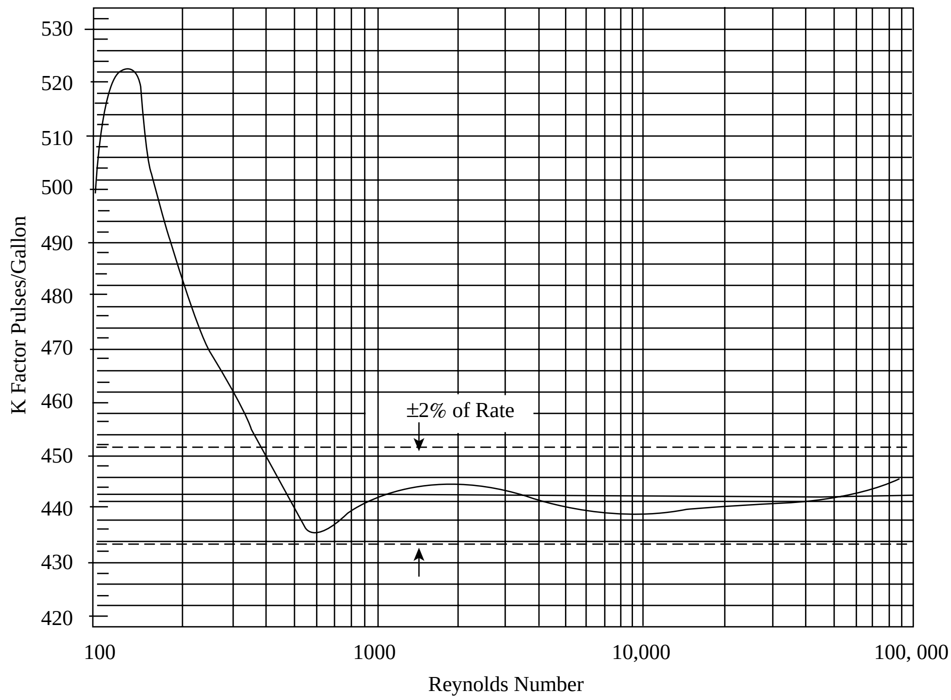


FIG. 2.30n
The meter factors of a 1-in. (25.4-mm) fluidic flowmeter stay accurate at lower values of Reynolds numbers than they do for vortex-shedding flowmeters. (Courtesy of Mycrosensor Inc.)

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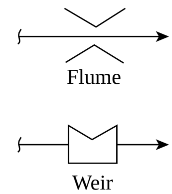
2.31 Weirs and Flumes

W. H. HOWE (1969, 1982) **B. G. LIPTÁK** (1995) **A. V. PAWLOWSKI** (2003)



Flow Sheet Symbol

Types	Open-channel flow can be measured by detecting level in front of primaries. Bubblers, capacitance, float, hydrostatic, and ultrasonic devices are used as level sensors. Open-channel flows can also be measured without primaries by calculating flow from depth and velocity using ultrasonic and magnetic sensors.
Operating Conditions	Atmospheric
Applications	Waste or irrigation water flows in open channels
Flow Range	From 1 GPM (3.78 l/m), no upper limit
Rangeability	Most devices provide 75:1; V-notch weirs can reach up to 500:1
Inaccuracy	Laboratory devices: 2 to 3% of full scale Field installations: 5 to 10% of full scale
Costs	Primaries used in pipe inserts cost less than $1000. A 6-in. (150-mm) Parshall flume costs about $1500, and a 48-in. (1.22-m) one costs about $5000. Primaries for irrigation applications are usually field-fabricated. Manual depth sensors can be obtained for $300; local bubbler or float indicators for $750 to $1500; and programmable, transmitting, capacitance, *ultrasonic*, or bubbler units from $2000 to $3000. Open-channel flowmeters calculating flow (based on depth and velocity) range from $5000 to over $10,000.
Partial List of Suppliers	ABB Automation, Instrumentation Division (www.abb.com/us/instrumentation) (primaries) Badger Meter Inc. (www.badgermeter.com) (Parshall or manhole flume, ultrasonic and open-channel computing) Endress+Hauser Inc. (www.us.endress.com) (ultrasonic and capacitance) Fischer Controls Int. (ultrasonic) Flow Technology Inc. (www.ftimeters.com) GLI International (www.gliint.com) Hays Cleveland (www.hayscleveland.com) Kay-Ray/Sensall Inc. (www.thermo.com) (ultrasonic) Manning Environmental Corp. (www.manning-enviro.com) (primaries) Marsh-McBirney Inc. (www.marsh-mcbirney.com) (electromagnetic) Milltronics Inc. (www.milltronics.com) (ultrasonic) Montedoro-Whitney Corp. (open-channel flow by ultrasonics) MSR Magmeter Mfg. Ltd. (www.magmeter.com) (robotic magmeter probe for open channel) Princo Instruments Inc. (www.princoinstruments.com) (capacitance) Robertshaw Ind. Royce Instrument Corp. Sponsler Co. (www.sponsler.com) Thermal Instrument Co. (www.thermalinstrument.com) Thermo Polysonics (www.thermopolysonics.com)

WEIRS

Weirs are apertures in the top of a dam, across a channel through which flows the liquid to be measured (Figure 2.31a). The aperture may be rectangular (Figure 2.31b), trapezoidal (Figure 2.31c), or V-notch (Figure 2.31d). The special case of a trapezoidal weir with side slopes of 1:4 (Figure 2.31c) is known as a *Cippoletti weir*; this form leads to a simplified flow calculation. V-notch weirs generally have a notch angle from 30 to 90°, depending on required flow capacity.

The head is measured as the difference in level of the pool at an adequate distance upstream from the weir as compared to the horizontal crest of a rectangular or trapezoidal weir, or the bottom point of the V of a V-notch weir. Heads less than 0.1 ft (30 mm) for minimum measured flow or more than 1.0 ft (300-mm) for maximum flow are generally to be avoided,

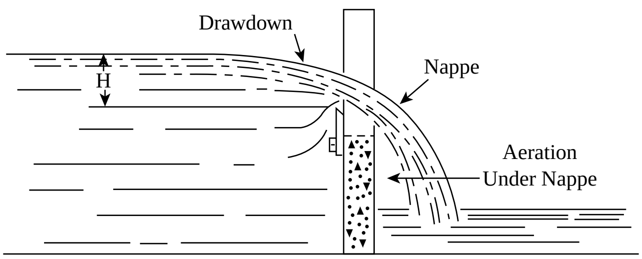


FIG. 2.31a
Flow over a weir.

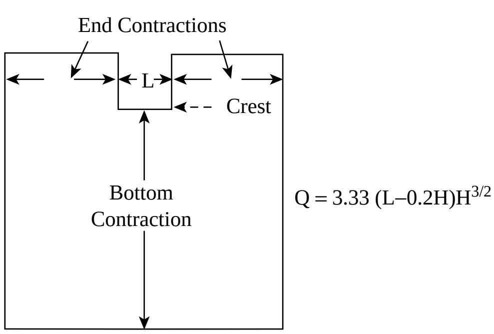


FIG. 2.31b
Rectangular weir.

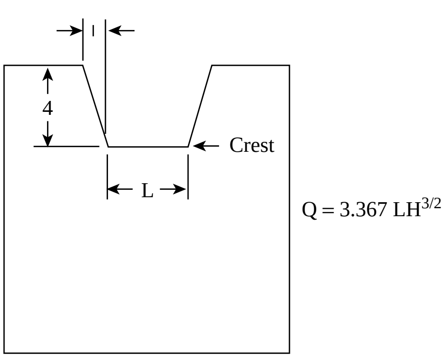


FIG. 2.31c
Cippoletti (trapezoidal) weir.

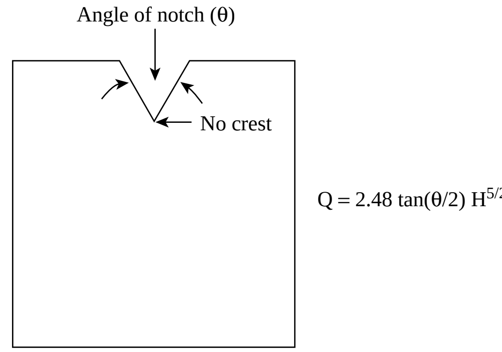


FIG. 2.31d
V-notch weir.

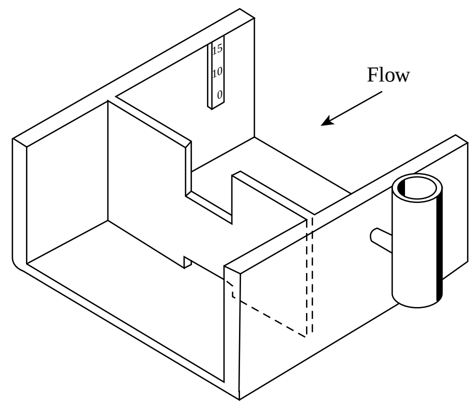


FIG. 2.31e
Weir box.

although a 1.25-ft (380-mm) head can be tolerated under favorable conditions. These limits are easily met by practical design, given that a 30° V-notch will measure a minimum flow of 1 GPM (3.8 l/m), whereas the maximum value for a rectangular or trapezoidal weir is limited only by practical crest length.

V-notch weirs are used for smaller flows. A 30° V-notch weir has a practically constant coefficient from 3.0 to 300 GPM (11.4 to 1140 l/min) with flow proportional to the five-halves power of the head. 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 notch angle up to 90°, flow varies as the tangent of half the notch angle. Notch angle exceeding 90° is not recommended.

Rectangular or Cippoletti weirs are used for larger flows. A rectangular weir with a crest 2 ft (0.6 m) long develops a head of about 0.2 ft (60 mm) for 250 GPM (946 l/min) and 1.0 ft (305 mm) for 2700 GPM (10,221 l/min). For this weir, flow is directly proportional to crest length and to the three-halves power of the head.

The weir plate may be located in a dam in a natural channel or in a weir box (Figure 2.31e). The stilling basin ahead of the weir should be large enough so that the upstream velocity does not exceed 0.33 ft/sec (0.01 m/sec). Width and depth immediately ahead of the weir should be sufficient so that the wall effect of the bottom and sides of the channel has negligible effect on the pattern of flow through the notch. It is important that the flow break clear from the sharp edge of the notch with an air pocket maintained immediately beyond and below the weir plate. The channel downstream from the weir must be sufficiently wide and deep so that, at maximum flow, there is ample clearance between flow through the notch to downstream liquid level so that this air pocket is maintained (Figure 2.31a). The upstream edge of the weir should be sharp and straight. It is usual practice to bevel the downstream edge of the weir at 45° to about a 1/32-in. (0.8-mm) edge. For rectangular and Cippoletti weirs, the crest must be carefully leveled.

Accuracy of the relation between flow and head (level) to ±2% is attainable, based on the dimensions of the primary device. Reference 1 gives full data on installation and operation of weirs.

The following equations establish the relationships between flow and measured head, provided that the installation and operation of the weir are as recommended in this section and also in the cited references.

For a V-notch weir

$$Q = 2.48\ \tan\frac{1}{2}\theta H^{2.5} \qquad \mathbf{2.31(1)}$$

For a rectangular weir

$$Q = 3.33(L - 0.2H)H^{1.5} \qquad \mathbf{2.31(2)}$$

For a Cippoletti weir

$$Q = 3.367\ LH^{1.5} \qquad \mathbf{2.31(3)}$$

where

Q = rate of flow in cubic feet per second
θ = V-notch angle in degrees
H = head* in feet of following liquid
L = crest length in feet

For conditions other than exactly as recommended, see references for correction factors.

THE PARSHALL FLUME

Developed by R.L. Parshall at the Colorado Experiment Station of the Colorado Agricultural College, in cooperation with the Division of Irrigation of the U.S. Department of Agriculture,[2] this device is a special type of venturi flume (Figure 2.31f). The loss of head is about one-quarter of that for a weir of equal capacity. Compared to weirs, approach velocity effects are practically eliminated so that a large upstream stilling basin is not required. The relatively high velocities in the system tend to flush away deposits of silt and other solids that might accumulate and alter measurement. There are no sharp edges, no pockets, and few critical dimensions; also, the device can be

* Head is measured between the level in the stilling pond and the crest of a rectangular or Cippoletti weir, or the bottom of the V of a V-notch weir.

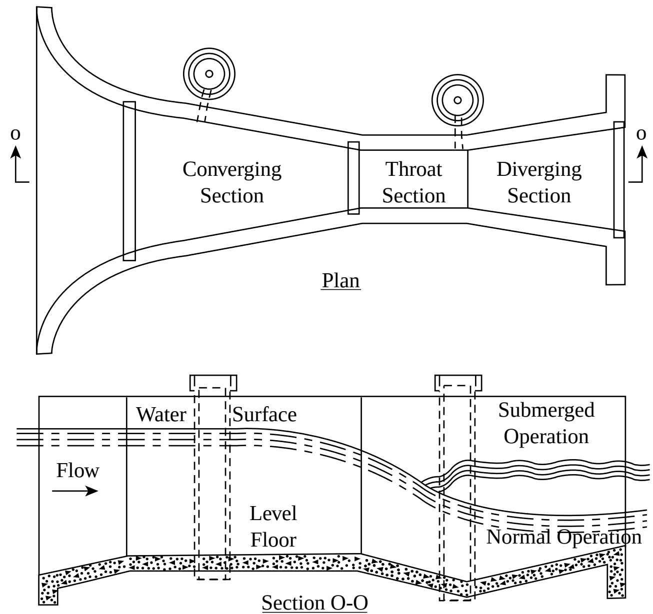


FIG. 2.31f
Parshall flume.

locally fabricated from available materials. Calibration data based on physical dimensions are available from 3 in. (76 mm) throat width with minimum range of 0.03 second-feet (13 GPM or 49 l/m) up to 50 ft (15.2 m) throat width with maximum capacity of 3300 second-feet (1,485,000 GPM/5,619,900 l/m). Flow is approximately proportional to the three-halves power of level with flow capacity of a single unit covering a range of 35:1 or more, depending on size.

Extreme accuracy is not claimed for flow measurement using this device; however, measurement is very dependable with minimal maintenance and good repeatability. Accuracy is adequate for most applications to irrigation, waste, and sewage flows.

Downstream level has minimal effect on the measurement as long as the level near the downstream end of the throat does not exceed 70% of the level measured near the upstream end of the converging section (Figure 2.31f). (Both levels are referred to the floor section of the flume.) For flumes less than 1 ft (305 mm) wide, the ratio of levels is 60% maximum. This is the preferred and more usual mode of operation. It provides best accuracy. Only one measurement of level is required, with flow computed directly from this upstream level measurement; direct, continuous readout of flow rate is readily provided.

Where operating conditions (available head, maximum flow rate, weir size, and so on) result in a throat level greater than 70% of upstream level, so-called *submersion* results. Measurement can be obtained with a downstream level as great as 95% of upstream level. However, this requires a correction factor based on both upstream level and downstream level in the flow computation, accuracy suffers, and special equipment is usually required for direct readout of flow.

The simplified equations based on a single measurement at the upstream location are as follows:

TABLE 2.31h
*Dimensions and Capacities of One-Piece Parshall Flumes**†

				Free Flow (GPM)	
Throat Width	Depth (inches)	Length	Weight (pounds)	Minimum	Maximum
2 in.	12	2 ft, 6.5 in.	35	9.0	210
3 in.	24	3 ft, 0 in.	40	13.5	494
6 in.	24	5 ft, 0 in.	100	22.4	1750
9 in.	30	5 ft, 4 in.	130	40.4	3950
12 in.	36	9 ft, 4.875 in.	280	157.0	7225
18 in.	36	9 ft, 7.875 in.	305	228.9	11,040
24 in.	36	9 ft, 10.875 in.	330	296.2	14,855
3 ft, 0 in.	36	10 ft, 4.075 in.	385	435.3	22,619
4 ft, 0 in.	36	10 ft, 10.375 in.	450	565.5	30,473
5 ft, 0 in.	36	11 ft, 10.25 in.	515	996.3	38,417
6 ft, 0 in.	36	11 ft, 10.375 in.	575	1180.3	46,450
7 ft, 0 in.	36	12 ft, 4.25 in.	650	1831.1	54,484
8 ft, 0 in.	36	12 ft, 10.125 in.	730	2073.5	62,607

*Units in table can be converted using 1 in. = 25.4 mm, 1 lb. = 0.45 kg; 1 in. H_2O = 249 Pa; 1 GPM = 3.785 l/min.
†Courtesy of ABB Inc.

For $L = 0.25$ ft,

$$Q = 3.97\ LH^{1.547} \tag{2.31(4)}$$

For $L = 0.5$ ft,

$$Q = 4.12\ LH^{1.58} \tag{2.31(5)}$$

For $L = 0.75$ ft,

$$Q = 4.10\ LH^{1.53} \tag{2.31(6)}$$

For $L = 1$ to 8 ft,

$$Q = 4.0\ LH(1.522L)^{0.026} \tag{2.31(7)}$$

For $L = >8$ ft,

$$Q = (2.5 + 3.69\ L)H^{1.6} \tag{2.31(8)}$$

where
L = width of throat section in feet
Q = volume flow rate in cubic feet per second
H = head in feet*

Parshall flumes are available in plastic construction. One variation of the plastic units is the nested, dual-range configuration in which two flumes are nested inside each other. This configuration is used in installations where the start-up conditions are substantially lower than the final operating flow rates (Figure 2.31g). With these units, the flow initially passes through the inner flume; then, when the flow exceeds its capacity, the inner flume is removed while the outer flume remains in place permanently. Dimensions of fiberglass-reinforced resin Parshall flumes are given in Table 2.31h.

* H (head) is measured at a designated point in the upstream converging section, referred to the level floor of this section.

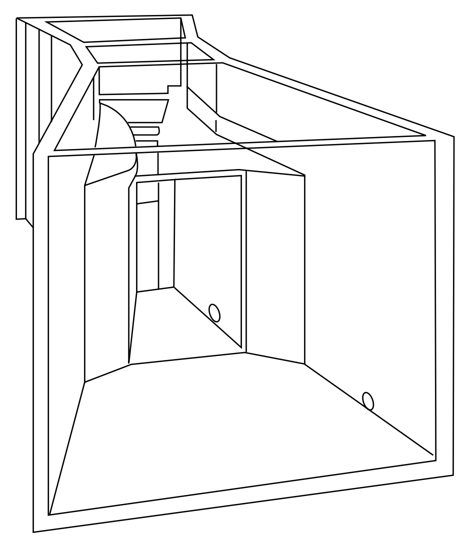


FIG. 2.31g
Dual-range Parshall flume. (Courtesy of ABB - Fischer & Porter Co.)

THE PALMER BOWLUS FLUME

Palmer-Bowlus flumes provide the advantages of rounded bottoms and relatively small size. Compared with other flumes, this makes for easier installation in pipe inverts, ends, and sewer manholes. They also have a smaller head change vs.

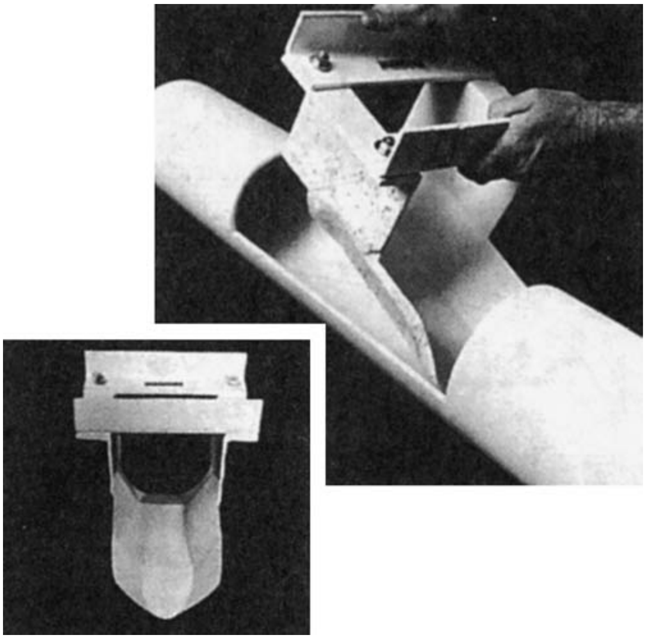


FIG. 2.31i
Flume insert elements. (Courtesy of Manning Environmental Corp.)

flow, and their dimensions are scalable to throat width, which makes rating of off-size flumes possible. A disadvantage is that the throat is raised; therefore, the possibility exists for upstream silt deposition at low flows. Reference 3 provides data on this.

These flumes are available for installation in existing round pipe using the type of insert shown in Figure 2.31i.

THE KENNISON NOZZLE, PARABOLIC FLUME, AND LEOPOLD LAGCO FLUME

These are typical proprietary products that were designed primarily for end-of-pipe flow measurement of waste, sewage, and the like, where the liquid flow to be measured emerges from a cylindrical pipe or conduit that usually is not completely full of liquid. All are designed to flush solids through the device without accumulations and to allow accessibility for inspection and cleaning if necessary.

These devices develop heads that are a function of flow rate. In the Kennison nozzle, head is almost linear with flow above 10% of maximum flow rate. Accuracy is stated as 2% in this range. For the parabolic flume and the Leopold Lagco flume, flow varies approximately as the three-halves power of head.

These devices are available in medium to large sizes. Details as to structure, application, and characteristics are available from the manufacturers.

DETECTORS FOR OPEN-CHANNEL SENSORS

The level rise generated by flumes or weirs can be measured by nearly any of the level detectors described in Chapter 3, including such simple devices as the air or nitrogen bubblers (Section 3.2).

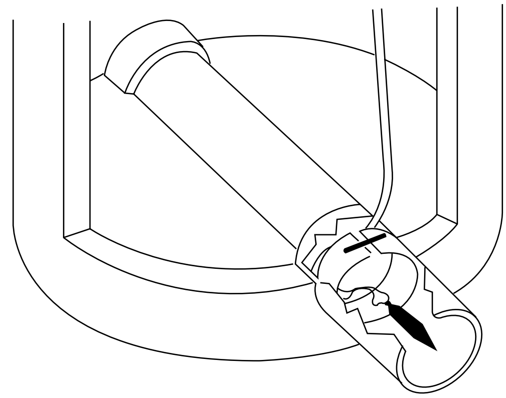


FIG. 2.31j
Volumetric flow computer measures depth and velocity in open channel and does not require a primary device. (Courtesy of Montedoro-Whitney Corp.)

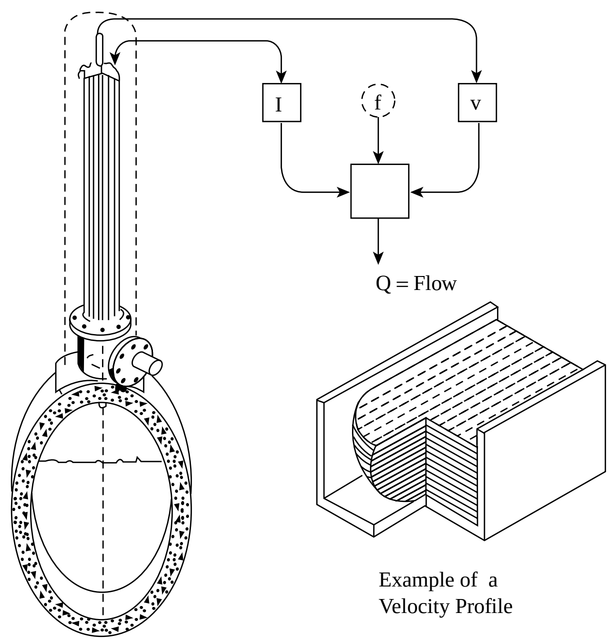


FIG. 2.31k
Robot-operated magnetic flow meter probe sensor is used to compute channel flow. (Courtesy of MSR Magmeter Mfg. Ltd.)

It is also possible to detect the flow in open channels without the use of flumes, weirs, or any other primary devices. One such design computes flow in round pipes or open channels by ultrasonically measuring the depth, calculating the flowing cross-sectional area on that basis, and multiplying the area by the velocity to obtain volumetric flow (Figure 2.31j).

Another open-channel flowmeter that does not need a primary element uses a robot-operated magnetic flowmeter probe to scan the velocity profile in the open channel (Figure 2.31k). In this design, the computer algorithm calculates and separately adds up the flow segments through each slice of the velocity profile as the velocity sensor moves down to the bottom of the channel.

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