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:

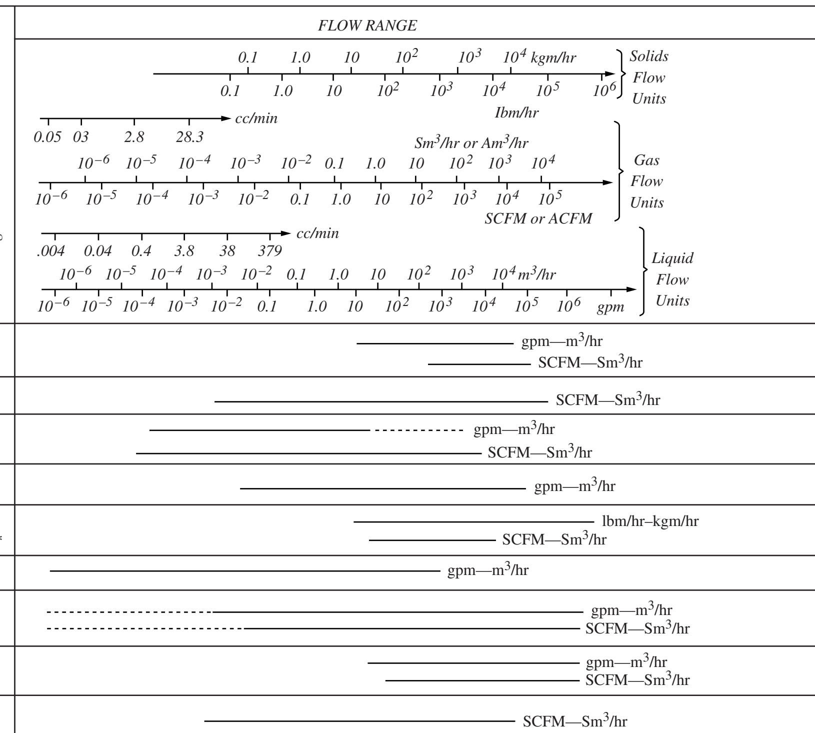
$$Q(\text{flow}) = K(\text{constant})\sqrt{\frac{h(\text{differential head})}{d(\text{fluid density})}} \qquad \textbf{2.1(1)}$$

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
Elbow Taps	✓	L	L	✓			✓	✓			✓	SR	3:1⑨	N	⑦25/10	5–10*	gpm—m^3/hr SCFM—Sm^3/hr
Jet Deflection				✓			✓	✓			✓	✓	25:1	N	⑦20/5	2*	SCFM—Sm^3/hr
Laminar Flowmeters	✓	✓		✓			✓	✓			✓	✓	10:1	H	15/5	1/2–5*⑧	gpm—m^3/hr SCFM—Sm^3/hr
Magnetic Flowmeters	✓⑤	✓⑤	✓⑤				✓	✓			✓	✓	10:1⑨	H	5/3	1/2**–2*	gpm—m^3/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—Sm^3/hr
Metering Pumps	✓	✓	✓				✓		✓		SD	✓	20:1	–	N	1/10–1*	gpm—m^3/hr
Orifice (Plate or Integral Cell)	✓	L	L	✓			✓	✓			✓	SR	3:1⑨	H	⑦20/5	1/2**–2*	gpm—m^3/hr SCFM—Sm^3/hr
Pitot Tubes	✓		L	✓			✓	✓			✓	SR	3:1⑨	M	⑦30/5	0.5–5*	gpm—m^3/hr SCFM—Sm^3/hr
Positive Displacement Gas Meters				✓			✓		✓	✓	SD	✓	10:1 to 200:1	M	N	1/2–1***	SCFM—Sm^3/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:

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

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:

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

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.

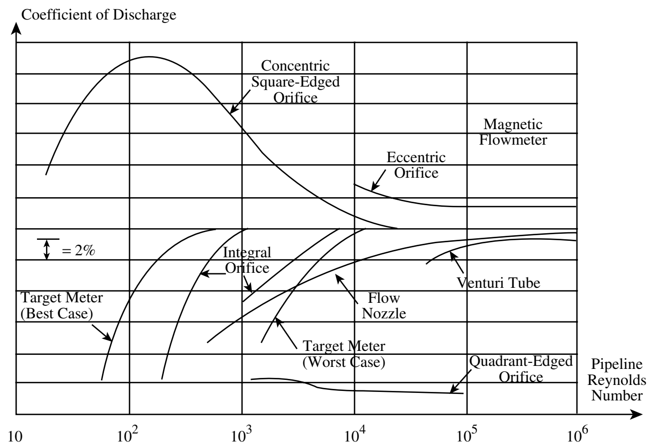


FIG. 2.1f
Discharge coefficients as a function of sensor type and Reynolds number. (Courtesy of The Foxboro Co.)

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).

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

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

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

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.

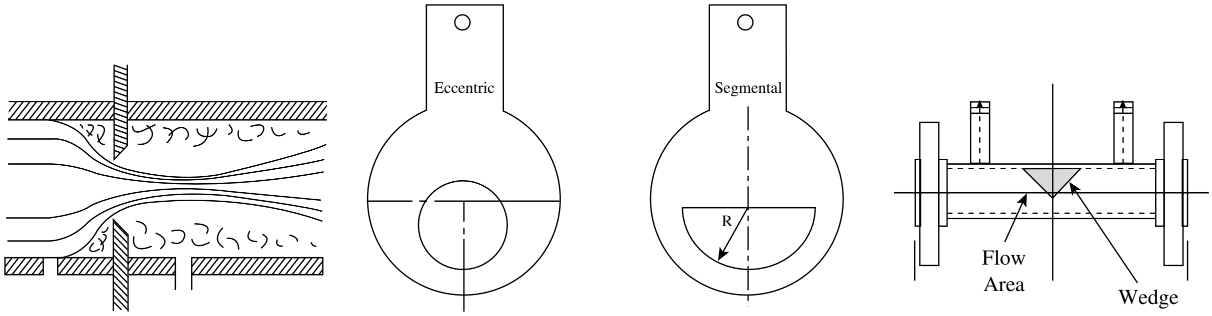
The main disadvantages are the low accuracy[5] (Figure 2.1i) and low rangeability of standard orifices, although substantial improvements been reported (error under 1% of actual flow over a 10:1 range) when intelligent and multirange d/p cells are used. Other disadvantages of orifice-type installations 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.

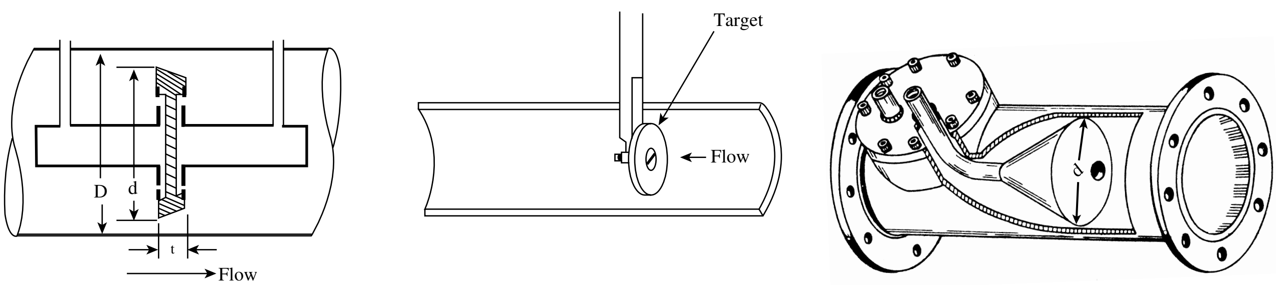
For paper pulp or slurry flow detection, the segmental and eccentric orifices (Section 2.15), venturi cones (Section 2.28) and the segmental wedge elements (Section 2.21) have been developed. The venturi cone is shaped as a restriction in the center of the flow path, forcing the flowing stream into an 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

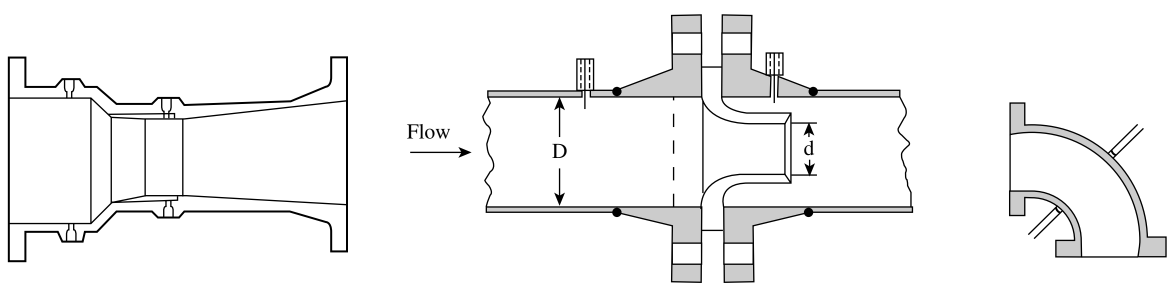
The shapes of these tubes and nozzles have been obtained with the goal of minimizing the pressure drop across them. These tubes are often installed to reduce the size of (and therefore capital expenditures on) pumping equipment and to save on pumping energy costs. In contrast with the sharp-edged



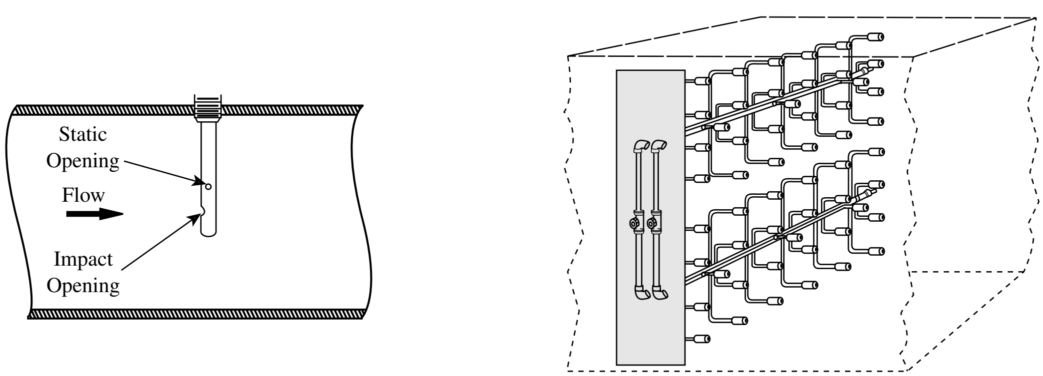
a) Sharp-edged, eccentric, segmental orifice and wedge designs



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.

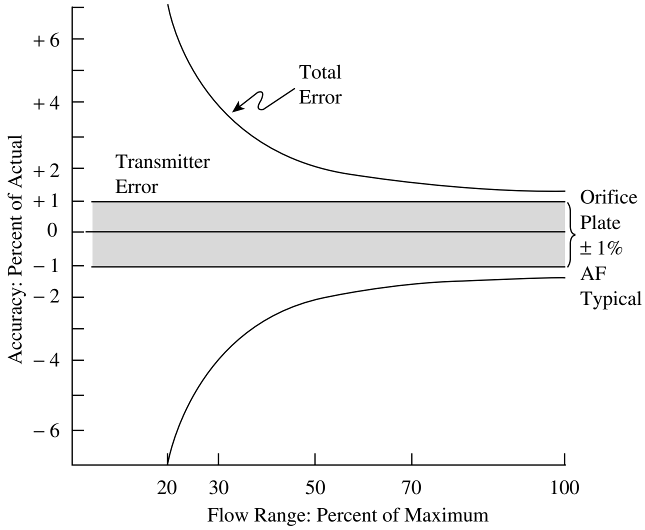


FIG. 2.1i
Total error of an orifice type flow measurement, using a ±1/2% full-scale d/p cell, is shown as a function of actual flow.

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

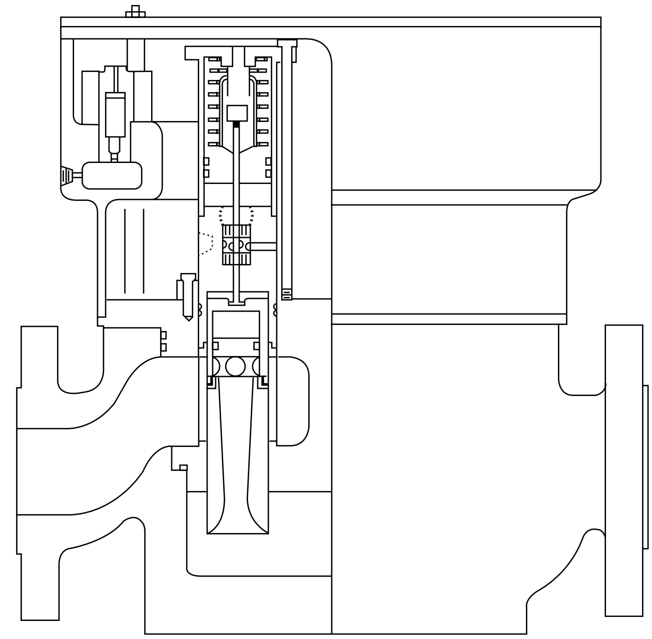


FIG. 2.1j
Sonic venturi digital flowmeter featuring extremely wide rangeability.

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.

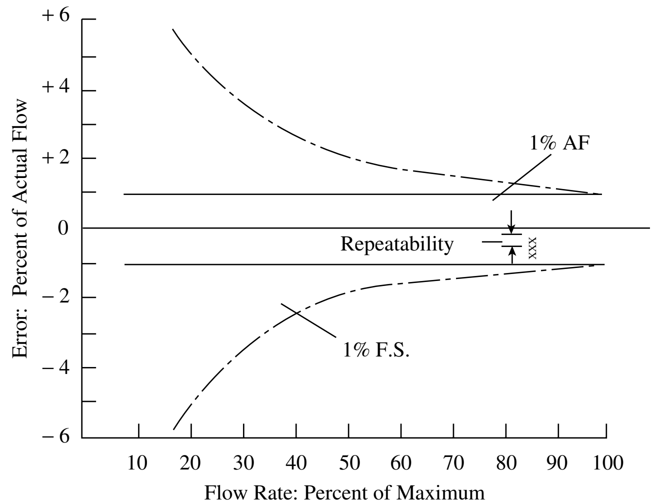


FIG. 2.1k
Comparison of 1% F.S. inaccuracy with 1% of flow inaccuracy.

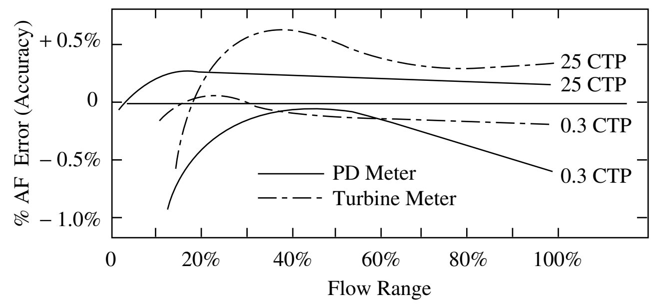


FIG. 2.1l
Differing effects of viscosity variation on a turbine meter and a positive displacement meter (CTP = centiPoises).

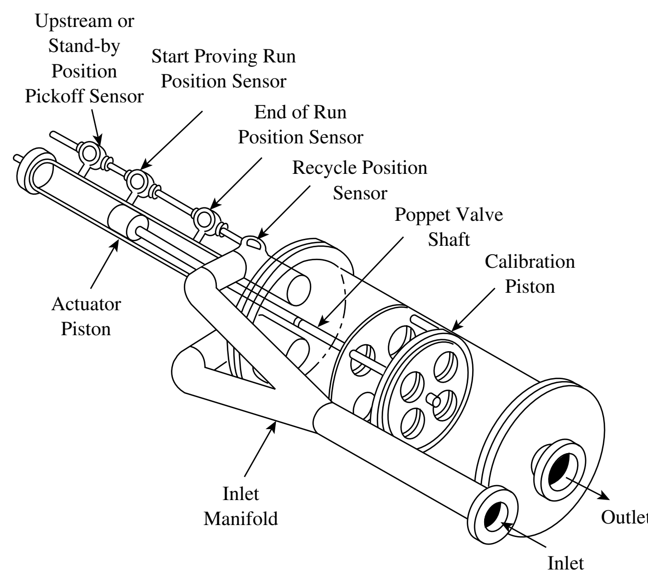


FIG. 2.1m
Inline ballistic flow prover. (Courtesy of Brooks Instrument Div. of Emerson Electric.)

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 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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