FLOW MEASUREMENT

1. Introduction

Flow measurement is a broad field covering a spectrum ranging from the minuscule flow rates associated with the pharmaceutical industry to the immense volume flows involved in water transfer and treatment. This measurement is an essential part of the production, distribution, consumption, and disposal of all liquids and gases including fuels, chemicals, foods, and wastes. The fluids to be measured may be pure compounds or contaminated mixtures, under vacuum or at high pressure, and at temperatures ranging from cryogenic to molten metal (see also FLUIDIZATION; FLUID MECHANICS). This breadth and diversity have led to the development of a multitude of flow measurement devices. All meet the requirements of certain applications and some achieve broad utility. None however come close to being universal in scope. The field of flow measurement is thus application oriented. The specific requirements of a particular measurement must be analyzed in detail before proper equipment selection can be made.

2. Flowmeter Selection

A number of considerations should be evaluated before a flow measurement method can be selected for any application. These considerations can be divided into four general classifications: fluid properties; ambient environment; measurement requirements; and economics.

2.1. Fluid Properties. A great variety of equipment exists for measuring clean, low viscosity, single-phase fluids at moderate temperatures and pressures. Fluid-related factors that are normally considered in selecting a particular type of meter are operating pressure, fluid temperature, viscosity, density, corrosive or erosive characteristics, flashing or cavitation tendencies, and fluid compressibility. Any extreme fluid characteristic or condition, such as a corrosive tendency or a high operating temperature, greatly reduces the range of available equipment and should be given first consideration in any selection procedure.

Other fluid properties are important only with certain meter types. For example, heat capacity is an important consideration in applying thermal meters while some fluid electrical conductivity is required when using magnetic flowmeters. In some cases, particular fluid requirements may limit the metering choices. An example of this is the requirement for the sanitary design of meters used in food processing (qv).

Reynolds Number. One important fluid consideration in meter selection is whether the flow is laminar or turbulent in nature. This can be determined by calculating the pipe Reynolds number, *Re*, a dimensionless number which represents the ratio of inertial to viscous forces within the flow.

$$q = \frac{\pi D^2}{4} V, \qquad Re = \frac{4eq}{\pi \mu D}$$

where ρ is the fluid density; μ is the fluid absolute viscosity; V is the average fluid velocity; D is the pipe or meter inlet diameter; and q is the volumetricflow rate. When q is in units of m^3/h, ρ in kg/m^3, D in m, and μ in Pa·s, the equation becomes

$$Re = \frac{(m^3/h)(kg/m^3)(\mathrm{m})}{2827(\mathrm{Pa{\cdot}s})}$$

When q is in gal/min, D in in., $\rho =$ specific gravity, and μ in cP,

$$Re = \frac{3160(\mathrm{gal/min})(\mathrm{in.})}{\mathrm{cP}}$$

A low Reynolds number indicates laminar flow and a parabolic velocity profile of the type shown in Figure 1**a**. In this case, the velocity of flow in the center of the conduit is much greater than that near the wall. If the operating Reynolds number is increased, a transition point is reached (somewhere over $Re = 2000$) where the flow becomes turbulent and the velocity profile more evenly distributed over the interior of the conduit as shown in Figure 1b. This tendency to a uniform fluid velocity profile continues as the pipe Reynolds number is increased further into the turbulent region.

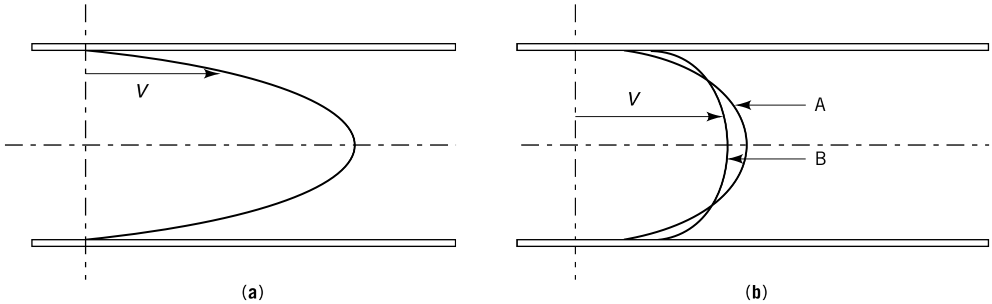


Fig. 1. Flow profiles, where V is velocity: (**a**) laminar, and (**b**) turbulent for fluids having Reynolds numbers of A, 2×10^5, and B, 2×10^6.

Most flowmeters are designed and calibrated for use on turbulent flow, by far the more common fluid condition. Measurements of laminar flow rates may be seriously in error unless the meter selected is insensitive to velocity profile or is specifically calibrated for the condition of use.

Ambient Environment. The environment around the flow conduit must be considered in meter selection. Such factors as the ambient temperature and humidity, the pipe vibration level, the availability of electric power, and the corrosive and explosive characteristics of the environment may all influence flowmeter selection. Special factors such as possible accidental flooding, the need for hosedown or steam cleaning, and the possibility of lightning or power transients may also need to be evaluated.

Enough space must be available to properly service the flowmeter and to install any straight lengths of upstream and downstream pipe recommended by the manufacturer for use with the meter. Close-coupled fittings such as elbows or reducers tend to distort the velocity profile and can cause errors in a manner similar to those introduced by laminar flow. The amount of straight pipe required upstream and, to a lesser extent downstream, depends on the flowmeter type. For the typical case of an orifice plate, piping requirements are normally listed in terms of the β or orifice/pipe bore ratio as shown in Table 1 (1) (see PIPING SYSTEMS).

A number of flow profile conditioning devices are available. These devices consist of multiple tubes, drilled plates or both. Conditioner manufacturers claim that their use can significantly reduce the amount of upstream straight pipe needed for accurate flow measurement using orifice plates or other meters.

2.2. Measurement Requirements. Any analysis of measurement requirements must begin with consideration of the particular accuracy, repeatability, and range needed. Depending on the application, other measurement considerations might be the speed of system response or the pressure drop across the flowmeter. For control applications, repeatability is normally the principal criterion; conversely for critical measurements, the total installed system accuracy must be considered. This latter includes the accuracy of the flowmeter and associated readout devices as well as the effects of piping, temperature, pressure, and fluid density. The accuracy of the system may also depend on the required measurement range.

Table 1. **Required Straight Pipe Lengths for Orifice Plates, Nozzles, and Venturis**[a]

	On upstream side of the primary device							
β	Single 90° bend or tee[b]	Two or more 90° bends in same plane	In different planes	Reducer[c]	Expander[d]	Globe[e] valve	Gate[e] valve	On downstream side[f]
0.20	10 (6)	14 (7)	34 (17)	5	16 (8)	18 (9)	12 (6)	4 (2)
0.25	10 (6)	14 (7)	34 (17)	5	16 (8)	18 (9)	12 (6)	4 (2)
0.30	10 (6)	16 (8)	34 (17)	5	16 (8)	18 (9)	12 (6)	5 (2.5)
0.35	12 (6)	16 (8)	36 (18)	5	16 (8)	18 (9)	12 (6)	5 (2.5)
0.40	14 (7)	18 (9)	36 (18)	5	16 (8)	20 (10)	12 (6)	6 (3)
0.45	14 (7)	18 (9)	38 (19)	5	17 (9)	20 (10)	12 (6)	6 (3)
0.50	14 (7)	20 (10)	40 (20)	6 (5)	18 (9)	22 (11)	12 (6)	6 (3)
0.55	16 (8)	22 (11)	44 (22)	8 (5)	20 (10)	24 (12)	14 (7)	6 (3)
0.60	18 (9)	26 (13)	48 (24)	9 (5)	22 (11)	26 (13)	14 (7)	7 (3.5)
0.65	22 (11)	32 (16)	54 (27)	11 (6)	25 (13)	28 (14)	16 (8)	7 (3.5)
0.70	28 (14)	36 (18)	62 (31)	14 (6)	30 (15)	32 (16)	20 (10)	7 (3.5)
0.75	36 (18)	42 (21)	70 (35)	22 (11)	38 (19)	36 (18)	24 (12)	8 (4)
0.80	46 (23)	50 (25)	80 (40)	30 (15)	54 (27)	44 (22)	30 (15)	8 (4)

[a] Nonparenthetical values are zero additional uncertainty. Parenthetical values are ±0.5% additional uncertainty. All straight lengths are expressed as multiples of the pipe diameter D. They are measured from the upstream face of the primary device.

[b] Flow from one branch only.

[c] $2D$ to D over a length of $1.5D$ to $3D$.

[d] $0.5D$ to D over a length of $1D$ to $2D$.

[e] Fully open.

[f] All fittings are included in this table.

Accuracies of flowmeters discussed herein are normally specified as either a percentage of the full-scale flow or as a percentage of the actual flow rate. It may be convenient in some applications to compare the potential inaccuracies in actual volumetric flow rates for different measurement devices. For example, in reading 2 L/min (LPM) on a flowmeter rated for five LPM, the maximum error for a $\pm 1\%$ of full-scale accuracy specification would be $0.01 \times 5 = \pm 0.05$ LPM. If another flowmeter of similar range, but having $\pm 1\%$ of actual flow rate specification, were used, the maximum error would be $0.01 \times 2 = \pm 0.02$ LPM. To minimize errors, meters having full-scale accuracy specifications should not be used at the lower end of their range. Whenever possible, performance parameters should be assessed for the expected installation conditions, not the reference conditions that are the basis of nominal product performance specifications.

2.3. Economic Considerations. The principal economic consideration in flowmeter selection is normally the total installed system cost. This includes the initial cost of the flow primary, flow secondary, and related ancillary equipment as well as the material and labor required for installation. Other typical considerations are the ongoing operating costs and the requirements for scheduled maintenance. An economic factor of increasing importance is the cost of disposal at the end of normal flowmeter service life. This may involve meter decontamination if hazardous fluids have been measured.

3. Flow Calibration Standards

Flow measuring equipment must generally be wet calibrated to attain maximum accuracy, and principal flowmeter manufacturers maintain extensive facilities for this purpose. A number of governments, universities, and large flowmeter users also maintain flow laboratories.

Calibrations are generally performed with water or air using one or more of four basic standards: weigh tanks, volumetric tanks, pipe provers, or master flowmeters. Most standards can be used statically, ie, where the flow is quickly started and stopped at the beginning and end of the test; dynamically, ie, where readings are taken at the instant the test is initiated and again at the instant it is completed; or in a hybrid dynamic start-and-stop static reading mode. Static systems operate best for flowmeters that have good accuracy at low flow rates and fast dynamic response. These methods do not give optimum results for vortex or turbine meters because of errors obtained during the short periods of low flow at the beginning and end of the test. Completely dynamic systems are limited by speed of response considerations and the general difficulties encountered using on-the-fly readings. Because of these limitations hybrid dynamic start-and-stop static reading weight and volume systems have been developed to provide more accurate liquid calibrations than purely static or dynamic systems. In such systems, the desired test flow rate is first obtained but diverted around the weight or volume standard. The test run is initiated by diverting the flow into the standard and completed by diverting it out of the standard. The weight or volume is then read after an appropriate settling time.

The key to the performance of a dynamic start-and-stop static reading system is the design of the flow diverter valve that switches the flow in and out of the standard. In a well-designed system the actual diversion time is much shorter than the collection time and the flow profile exiting the diverter relatively independent of flow rate. Under these circumstances, the limiting factor in system accuracy is the basic accuracy and resolution of the weight or volume standard. Errors can be reduced to <0.1% of actual flow rate. Calibration systems of this type are generally restricted to large test facilities because of the high cost involved.

3.1. Liquid Displacement Gas Meter Provers. The liquid displacement prover is the most prevalent standard for the calibration of flowmeters at low to moderate gas flow rates. The method consists of displacing a known volume of liquid with gas (Fig. 2). Gas entering the inverted bell causes it to rise and a volume increment can be timed. Typical prover capacities are 1 m^3 or less although capacities as large as 20 m^3 are available. Accuracies can be on the order of 0.5% of actual flow rate.

3.2. Pipe Provers. In pipe proving systems a sealed piston or elastic sphere is driven through a pipe section of precise bore using either the fluid energy or external activation. This measuring section may be coupled into the process pipe or part of a portable closed loop also containing the meter under test. Piston travel is detected to establish calibration volume. On closed-loop systems valves normally permit bidirectional actuation. Figure 3 shows one form of a commercial closed-loop prover system. In this system temperature and pressure inputs are used to compute fluid density changes and provide an overall accuracy rating of up to 0.05% of actualflow rate.

Liquid provers are available for use with flow rates from ∼0.005 up to rates of thousands of LPM. They are suitable for clean liquids of almost any viscosity.

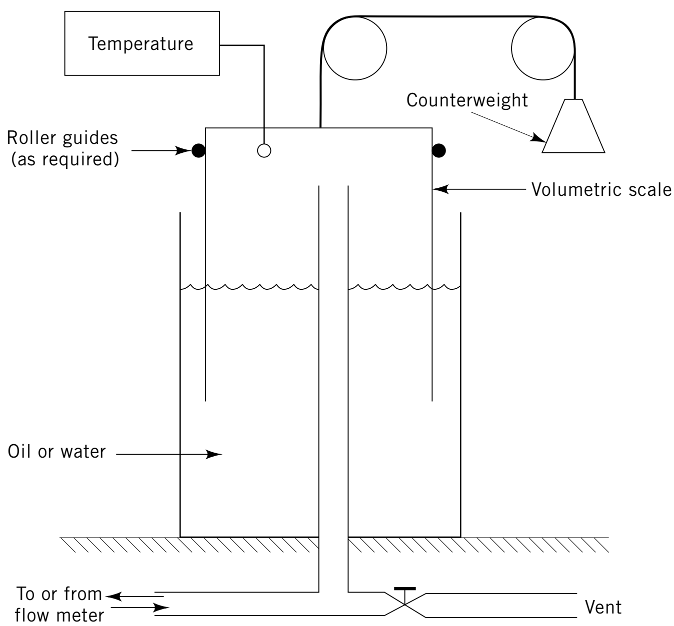


Fig. 2. Liquid displacement calibrator.

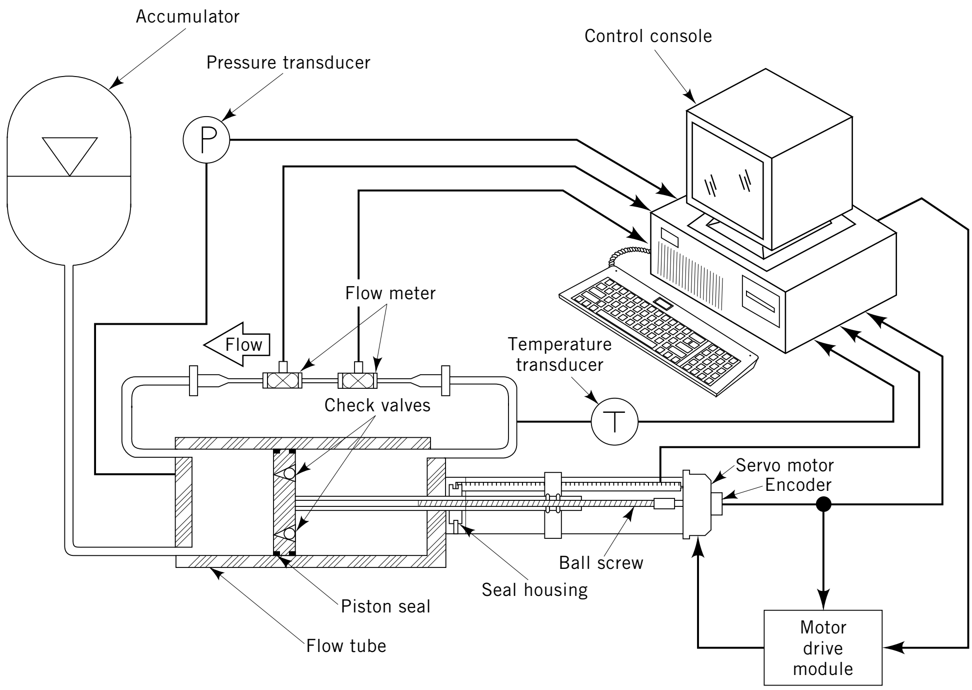


Fig. 3. Comtrack 921 pipe prover. Liquid flow through the Comtrak's closed loop is created by the movement of a sealed piston. Flow meters being tested are installed in the loop upstream from the piston. As the piston advances, the calibration fluid travels through the meters and returns to the back side of the piston.

Prover systems are relatively compact and rugged. These features, combined with accuracy, result in wide usage in the custody transfer of petroleum (qv) products. Many open-loop-type pipe provers are permanently installed in pipeline metering stations where these provers are used to check operating meters (see PIPELINES). The readings have a high economic impact, affecting the transfer of large sums of money. Self-contained proving systems are also commonly used as flow laboratory standards.

3.3. Master Flowmeters. Perhaps the most common method of flowmeter calibration is to compare the output of the meter under test with one or more meters of high resolution and proven accuracy, called master flowmeters. This method is both convenient and quick. To obtain optimum accuracy, a system can be set up using multiple masters of overlapping range where the masters are regularly compared against each other and periodically calibrated using weight or volume standards. This combines the convenience of the master meter method and the accuracy capability of the basic standard (2).

4. Flowmeter Classifications

Flowmeters have traditionally been classified as either electrical or mechanical depending on the nature of the output signal, the power requirements, or both.

Improvements in electrical transducer technology have blurred the distinction between these categories. Many flowmeters previously classified as mechanical are now used with electrical transducers. Some common examples are the electrical shaft encoders on positive displacement meters, the electrical (strain) sensing of differential pressure, and the ultrasonic sensing of weir or flume levels.

The flowmeters discussed herein are divided into two groups based on the method by which the basic flow signal is generated.

The first group consists of meters in which the signal is generated from the energy of the flowing fluid. A differential-pressure meter is a typical example of a self-generating flowmeter.

The second group of flowmeters comprises those meters that derive their basic signal from the interaction of the flow and an external stimulus. The manner in which the flow signal is transduced, conditioned, or transmitted does not determine the classification.An example of this type is the Electromagnetic Flowmeter which derives a voltage signal proportional to flow rate from the interaction of the flow with an electromagnetic field.

Meters can be further divided into three subgroups depending on whether fluid velocity, the volumetric flow rate, or the mass flow rate are measured. The emphasis herein is on common flowmeters. Devices of a highly specialized nature, such as biomedical flowmeters, are beyond the scope of this article.

5. Fluid Energy Activated Flowmeters

5.1. Positive-Displacement Flowmeters. Positive-displacement flowmeters separate the incoming fluid into chambers of known volume which, using the energy of the fluid, advance through the meter and discharge into the downstream pipe. The total volume of fluid passing through the meter is the product of the internal-meter swept volume and the number of fillings. Meter sizing is based on the relationship between flowmeter capacity, pressure drop across the meter, and fluid viscosity (3).

Positive-displacement meter chambers are housed in a pressure-containing vessel that may be of single- or double-wall construction. In single-wall construction, the housing forms part of the measuring chamber walls. In double-wall construction the housing is separate from the measuring portion and serves only as a pressure vessel. Double-wall construction has two distinct advantages: first, chamber walls can be thinner and more precisely formed as these do not need to withstand the full fluid static pressure; second, this construction allows piping stress to be confined to the external housing leaving the chambers free of potentially distorting forces.

The output signal from positive-displacement meters may be mechanical, where the motion is transmitted by an output shaft through a housing seal, or it may be magnetically or inductively coupled.

All positive-displacement meters depend on very close clearance dimensions between rotating and moving parts and thus are not suitable for fluids containing abrasive particles. These meters have broad application in the distribution of natural gas for two reasons: the completely mechanical nature and the ability to maintain good accuracy over long periods of time. Wear in positive-displacement meters tends to increase leakage so that errors are in the direction of underregistration, the most acceptable mode of error for commercial billing meters within the gas industry. Meters are normally periodically recalibrated and adjusted to read within 1% of the actual volumetric flow.

Positive-displacement meters also find broad application in the measurement of viscous liquids because high viscosities provide lubrication and minimize seal leakage. Positive-displacement designs are inherently insensitive to incoming velocity profile and thus to piping configuration and Reynolds number. They normally do not require specific upstream or downstream piping. Good accuracy can be obtained at conditions of transitional Reynolds numbers where many other meters exhibit nonlinearity.

Positive-displacement meters are normally rated for a limited temperature range. Meters can be constructed for high or low temperature use by adjusting the design clearance to allow for differences in the coefficient of thermal expansion of the parts.

Owing to small operating clearances, filters are commonly installed before these meters to trap entrained particles, minimizing seal wear and resulting loss of accuracy.

There are at least five types of positive-displacement meters commercially available.

Reciprocating Piston Meters. In positive-displacement meters of the reciprocating piston type, one or more pistons similar to those in an internal-combustion engine are used to convey the fluid. Capacity per cycle can be adjusted by changing the piston stroke.

Bellows or Diaphragm Meters. Bellows meters use flexible diaphragms as the metering chambers. A series of valves and linkages control the filling and emptying of the chambers. Movement of the flexible walls is regulated for a constant displacement per stroke. Meters of this type are widely used in the gas industry as residential meters (see GAS, NATURAL).

Nutating Disk Meters. In positive-displacement meters of nutating disk design, the chambers are formed by a disk mounted on a central ball. The disk is held in an inclined position so that it is in contact with the chamber bottom along a radial section on one side of the ball and in contact with the top at a section 180° away. A radial partition prevents the disk from rotating about its own axis. Inlet and outlet ports are located on each side of the partition. Liquid alternately enters above and below the disk and flows around the conical chamber toward the outlet port. This movement causes the disk to nutate, ie, to undergo a circular nodding motion. This disk motion is coupled to a mechanical meter register that integrates volumetricflow rate. Nutating disk meters are mechanically simple and rugged. They are widely used as commercial water meters.

Rotary Impeller Vane and Gear Meters. One group of positive-displacement meters depends on shaped impellers or gears to form the measuring chambers. Figure 4 illustrates a two-lobed rotary meter of the type used to measure gas flow. The impellers are designed to maintain a continuous seal during rotation. Close tolerances and the use of precision bearings permit these meters to have minimal leakage while keeping overall pressure loss low. Rotating-vane meters are somewhat similar in design but include a timed gate to isolate the

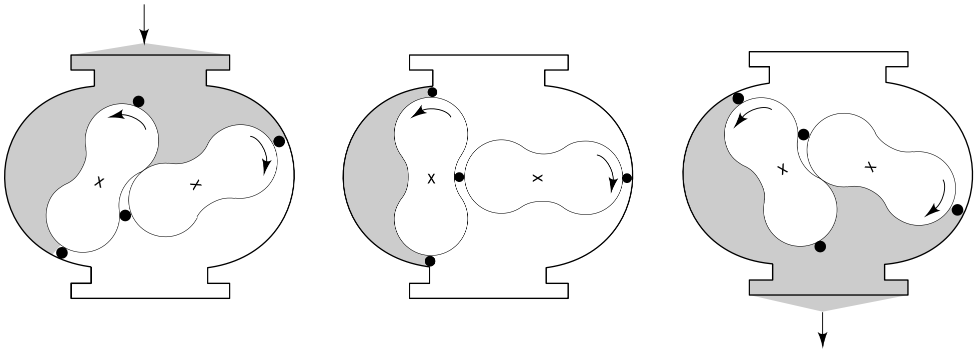


Fig. 4. Operating sequence for a two-lobed rotary gas flow meter where the shaded area represents the flowing fluid.

inlet and outlet ports. Figure 5 shows one cycle of a rotating-vane gas meter. The pressure of the entering gas rotates the vane assembly counterclockwise and, through timing gears, rotates the gate. In successive positions, the annular segment of gas is isolated by vanes 1 and 2, rotated through the housing, and discharged by the action of the gate.

5.2. Differential-Pressure Flowmeters. Differential-pressure or variable head flowmeters are the oldest, most common group of flow measurement devices. This general category includes orifice plates, venturi tubes, flow nozzles, elbow meters, wedge meters, pitot tubes, and laminar flow elements. All are based on the Bernoulli principle: in a flowing stream, the total energy, ie, the sum of the pressure head, velocity head, and elevation, remains constant. Differential-pressure devices all create some restriction in the fluid conduit causing a temporary increase in fluid velocity and a corresponding decrease in local head or pressure. For these conditions, the Bernoulli principle can be applied to give a general equation for head meters:

$$q = kA(2gh)^{1/2}$$

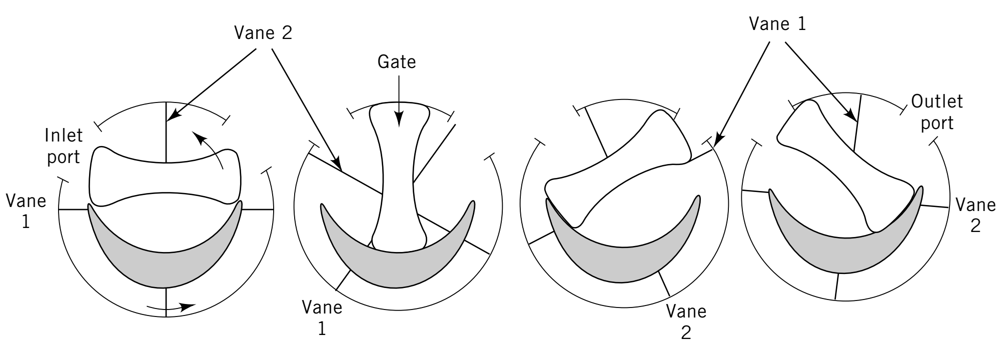


Fig. 5. Operating sequence for a rotating-vane positive-displacement meter.

where q is the volumetric rate of flow; k is the dimensionless experimentally determined flow coefficient; A is the inside cross-sectional area of the pipe; h is the differential produced by the restriction measured in height of the flowing fluid; and g is the gravitational constant.

The basic form of the equation is normally modified so that the differential is expressed in pressure units and the flow coefficient is divided into the product of an experimentally determined discharge coefficient, K, and a series of calculated coefficients. In this form, for concentric restrictions:

$$q = K\beta^2 AYFa2g\left(\frac{P_1 - P_2}{\rho}\right)^{1/2}$$

where β is the ratio of the restriction to the pipe diameter, d/D, known as the beta ratio; Y, the gas expansion factor for an adiabatic charge from P_1 to P_2; P_1 is the upstream pressure; P_2, the restriction pressure; Fa is the thermal expansion factor for the restriction; ρ is the fluid density; and K is the discharge coefficient.

An outstanding advantage of common differential pressure meters is the existence of extensive tables of discharge coefficients in terms of beta ratio and Reynolds numbers (1,4). These tables, based on historic data, are generally regarded as accurate to within 1–5% depending on the meter type, the beta ratio, the Reynolds number, and the care taken in manufacture. Improved accuracy can be obtained by running an actual flow calibration on the device.

Improvements in low differential readout devices and the desire to minimize permanent pressure losses have resulted in a trend toward higher beta devices. This is generally at the price of increased sensitivity to upstream piping configuration (see Table 1). To obtain accurate differential-pressure measurements, the installation should conform as closely to reference conditions as possible. The pipe should be inspected with respect to diameter, roundness, smoothness, and tap location. The fluid restriction should be mounted concentric to the pipe internal diameter and any gaskets required cut so as not to protrude into the flow stream. Both pressure taps should be of the same diameter with no roughness or burrs. The pressure lines must be carefully installed in accordance with the guidelines in Ref. 5. Improperly installed lines are probably the most common cause of orifice measurement errors. The differential-pressure transmitter should be as close to the taps as possible and the coupling lead lines sloped to permit condensate or gas bubble removal.

In liquid service the lines must constantly slope downward toward the transmitter from the taps to prevent possible gas pockets. In gas service the lines should drain to prevent condensate accumulation or, if the condensate is used to transmit the pressure from the taps to transmitter, the condensate legs must be of equal height.

Orifice Plates. The various types of traditional orifice plates are shown in Figure 6. A square-edge orifice, the most commonly applied type, is a thin flat plate set perpendicular to the flow with a clean, sharp edged circular opening. This opening is normally concentric with respect to the pipe centerline, although eccentric plates having the opening tangent to the pipe axis are often used for steam (qv), gas with entrained liquids, or sediment bearing fluids. Segmented

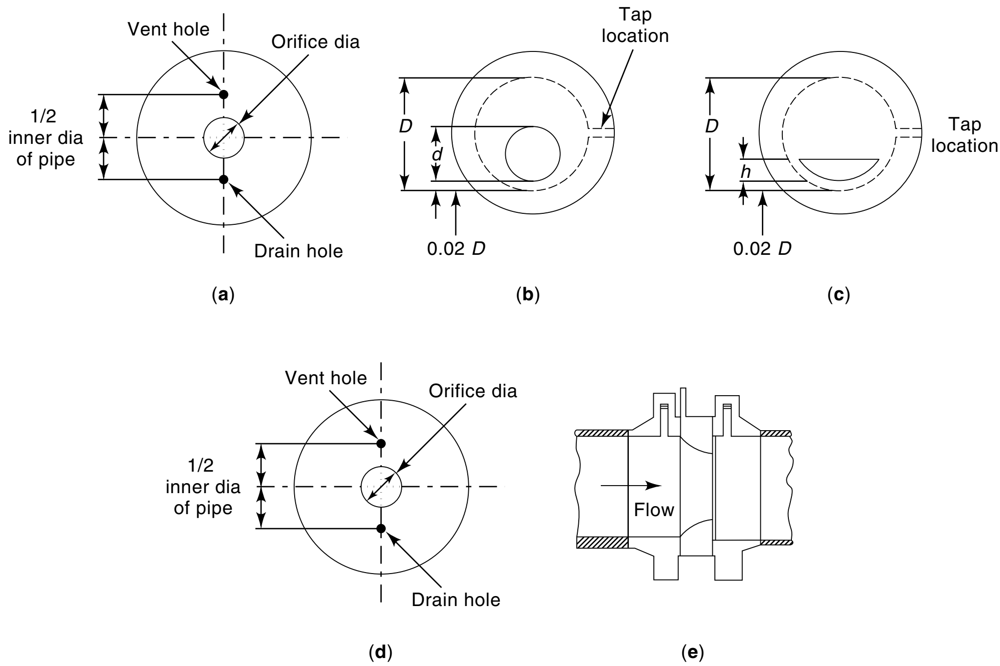


Fig. 6. Orifice plates: (**a**) concentric, (**b**) eccentric, (**c**) segmental, (**d**) universal, and (**e**) quadrant-edge.

orifice plates having the opening in the shape of a circular segment are applied to viscous flows and slurries. At pipe Reynolds numbers <10,000 the coefficient of discharge for a square edge orifice tends to become nonlinear and quadrant edge orifices are commonly used. These are thicker plates where the inlet edge is rounded making them less sensitive to fluid viscosity effects. For example, the change in discharge coefficient for a quadrant-edge orifice between Reynolds numbers of 5,000 and 10,000 is $\sim$2% compared with a change several times greater for a sharp edged orifice over the same *Re* range.

Conditioning orfice plates are now available that feature multiple small openings rather than a single opening. The manufacturers claim discharge coefficient accuracies of 0.5% with as little as two diameters of straight upstream piping.

There are five locations in use for the taps used to couple the differential to the measurement device. These locations are depicted in Figure 7. Corner taps, drilled in the orifice mounting flanges on either side and as close to the plate as possible, are commonly used in Europe for pipe sizes under 50 mm. Flange taps, each located 25 mm from the respective faces of the plate, are easily constructed and in greatest general use. For larger size pipes, radius taps, or D and $D/2$ taps, are located 1 pipe diameter upstream and 0.5 pipe diameters downstream from the upstream face of the plate. These taps are normally used in North America for small pipe sizes. Pipe taps (not shown) are located 2.5 pipe diameters upstream and 8 pipe diameters downstream from each plate face. This down-

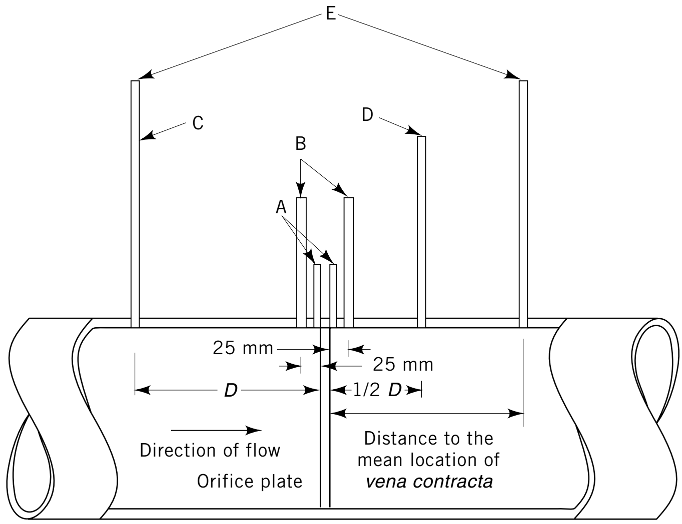


Fig. 7. Orifice plate pressure tap locations. A, corner taps; B, flange taps; C, *D* taps; D, 1/2 *D* taps; and E, *vena contracta* taps. See text.

stream connection increases orifice fitting length and limits usage of this type of tap.

The fifth type of tap is unique in that the downstream tap location varies depending of the orifice β ratio. This tap is located at the *vena contracta*, the location where the stream issuing from the orifice attains its minimum cross section. The location of this tap is defined from the upstream face of the orifice as is the $D/2$ tap. The downstream tap for corner, flange, and pipe taps is measured from the downstream face of the orifice. *Vena contracta* taps maximize the measured differential pressure. For modern transmitters this is not an important consideration and this type of tap is no longer widely used.

For very low flow rates the orifice plate is often incorporated into a manifold, an integral part of the differential-pressure transmitter. This provides a convenient compact installation.

Two equations for the calculation of square-edge orifice coefficients are in general use: one discharge (4) is based on extensive calibrations performed in the 1930s and is widely used in natural gas measurement; the second is accepted by the American Society of Mechanical Engineers (ASME) and the International Organization for Standardization (ISO) (1). In larger pipes the difference between the coefficients calculated by these two methods is generally small (6).

Orifice plates should be periodically inspected for signs of edge wear, warping, scratches, and deposits, any of which may result in a loss of accuracy from a change in discharge coefficient. Orifice plates have the advantages of being simple, hydraulically predictable, readily interchangeable, and reliable. These meters find wide use in both liquid and gas service where moderate accuracy and limited range meet the needs of many applications.

Venturi Tubes. A venturi tube consists of two hollow truncated cones, the smaller diameters of which are connected by a short circular section known as the throat. Pressure differential is measured between the upstream and throat sections and can be related to flow from equations or tables in a manner similar to orifice plates. The sole purpose of the downstream cone is to recover part of the differential pressure. For an exit cone angle of 7%, the permanent pressure loss is only ~10% of the differential. A number of short-tube, larger exit angle venturi tubes are commercially available; these require less space for installation but have a higher permanent pressure loss. Advantages of venturi tubes relative to orifice plates are the lower permanent pressure drop and reduced sensitivity to dirty flow conditions of the former. The smooth contours of a venturi allow entrained particles to flow past instead of building up as these do when an orifice is used. Disadvantages of the venturi are greater cost, longer installation length, and lack of easy interchangeability.

Flow Nozzles. A flow nozzle is a constriction having an elliptical or nearly elliptical inlet section that blends into a cylindrical throat section as shown in Figure 8. Nozzle pressure differential is normally measured between taps located 1 pipe diameter upstream and 0.5 pipe diameters downstream of the nozzle inlet face. A nozzle has the approximate discharge coefficient of an equivalent venturi and the pressure drop of an equivalent orifice plate although venturi nozzles, which add a diffuser cone to proprietary nozzle shapes, are available to provide better pressure recovery.

Flow nozzles are commonly used in the measurement of steam and other high velocity fluids where erosion can occur. Nozzle flow coefficients are insensitive to small contour changes and reasonable accuracy can be maintained for long periods under difficult measurement conditions that would create unacceptable errors using an orifice installation.

Critical Nozzles. As the pressure differential across a nozzle or venturi is increased the rate of discharge of a gas also increases until the linear velocity in the throat reaches the velocity of sound. Any further increase in pressure differential does not cause an increase in velocity. In this condition the nozzle is referred to as choked or at critical flow. The ratio of downstream/upstream pressure where critical flow is first obtained is called the critical pressure ratio, R_c. For nozzles of the shape shown in Figure 8, R_c is approximately equal to 0.5 but

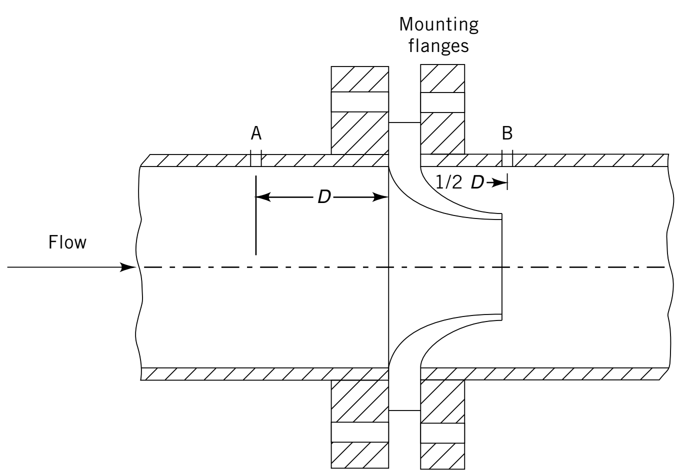


Fig. 8. Flow nozzle showing A, the high pressure tap, and B, the low pressure tap.

the addition of a venturi-type outlet can provide pressure recovery so that values of R_c as high as 0.96 can be obtained. As long as critical conditions are maintained only the upstream pressure and temperature are needed to determineflow rate. Nozzles operated at critical conditions are rugged and provide repeatable measurements; they make a good standard for the calibration of other gas flowmeters. One principal application area is in the low flow testing of automotive carburetor and emission-control systems (see EXHAUST CONTROL, AUTOMOTIVE). Critical nozzles are also widely used at high gas flow rates where actual nozzle calibration is impractical. For these applications a theoretical discharge coefficient is used.

Elbow Meters. Fluid passing through a common pipe elbow generates a differential pressure between the inside and outside of the elbow resulting from centrifugal force. This differential can be measured to provide an estimate of flow, on an uncalibrated elbow, to ~4% uncertainty. Experimental tests indicate the elbow flow coefficient to be insensitive to changes in relative elbow roughness. Elbow differentials are generally used for the balancing of flow rates in multiple manifold systems or in efficiency testing.

Wedge Meters. The wedge flowmeter consists of a flanged or wafer-style body having a triangular cross section dam across the top of the fluid conduit. Pressure taps are on either side of this restriction. Overall meter sizes range from 10 to 600 mm. Within each size several restrictions are available to provide the range of differential pressure desired for the application.

The wedge design maintains a square-root relationship between flow rate and differential pressure for pipe Reynolds numbers as low as ~500. The meter can be flow calibrated to accuracies of ~1% of actualflow rate. Accuracy without flow calibration is ~5%.

The wedge restriction has no critical surface dimensions or sharp edges and tends to retain accuracy despite visible corrosive or erosive wear. It is commonly applied to high viscosity liquids, slurries, and hot multiphase mixtures. A similar device is also available using a cone, positioned so that its large diameter is upstream, mounted on the meter centerline.

Pitot Tubes. The fundamental design of a pitot tube is shown in Fig. 9**a**. The opening into the flow stream measures the total or stagnation pressure of the stream whereas a wall tap senses static pressure. The velocity at the tip opening, V, can be obtained by the Bernoulli equation:

$$V = C(2g/(P_1 - P_2))^{1/2}$$

This equation is applicable for gases at velocities under 50 m/s. Above this velocity, gas compressibility must be considered. The pitot flow coefficient, C, for some designs in gas service, is close to 1.0; for liquids the flow coefficient is dependent on the velocity profile and Reynolds number at the probe tip. The coefficient drops appreciably below 1.0 at Reynolds numbers (based on the tube diameter) <500.

Standard pitot tubes provide a measurement of point velocity only; any attempt at determining total flow involves the assumption of a velocity profile. To overcome this disadvantage averaging pitot tubes have been developed. As

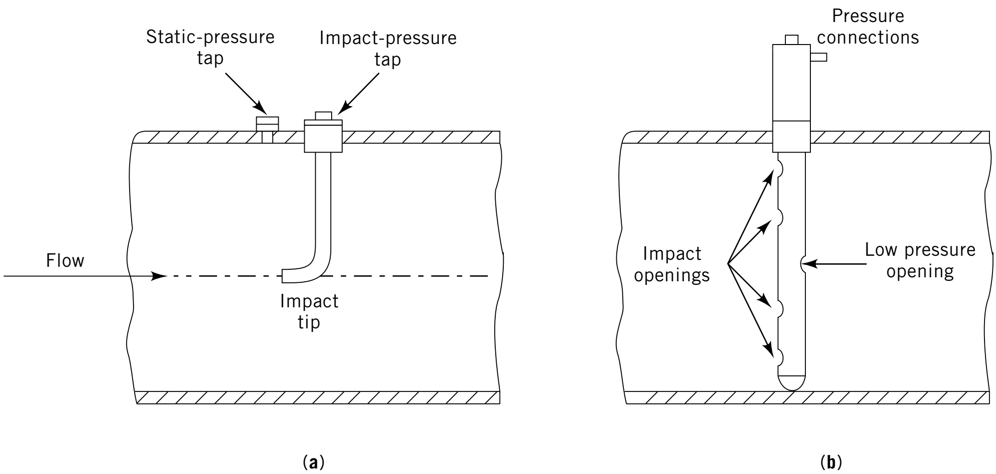


Fig. 9. Pitot tube designs: (**a**) basic and (**b**) averaging.

shown in Figure 9**b**, these tubes extend across the pipe and use a series of holes at specific annular spacing to obtain an average velocity along the probe length. A single downstream-facing opening senses the downstream pressure. Averaging pitot tubes now feature improved aerodynamic shapes to reduce process build-up on the back side of the bar.

The major application area for averaging pitot tubes is in measuring the air flow in large ducts.

Advantages of the pitot method of measurement are low pressure loss and easy installation. In some cases installation can be made in existing lines without process shutdown by hot tapping the line (7).

Laminar Flow Elements. Each of the previously discussed differential-pressure meters exhibits a square root relationship between differential pressure and flow; there is one type that does not. Laminar flowmeters use a series of capillary tubes, rolled metal, or sintered elements to divide the flow conduit into innumerable small passages. These passages are made small enough that the Reynolds number in each is kept <2000 for all operating conditions. Under these conditions, the pressure drop is a measure of the viscous drag and is linear withflow rate as shown by the Poiseuille equation for capilary flow:

$$\text{capillary flow} = \frac{\pi C D^4 (P_1 - P_2)}{128\,\mu L}$$

where D is the diameter of the capillary tube; L is the tube length; C is the experimentally determined flow coefficient; μ is the fluid viscosity; and P_1–P_2 is the differential pressure over the tube length L. Because of the small passage sizes and dependence on D^4, laminar flowmeters are suitable for use only with very clean fluids.

Differential pressure meters, like almost all flowmeters, measure volumetric flow although the user is often interested in mass flow. Incresingly, this need is being met by inferential mass measurement\using the combination of a differential producer and a multivariable transmitter. Current technology allows not only for pressure and temperature corrections to differential readings but also for compressibility algorithms such as the ANSI Steam Tables.

Target Flowmeters. Target flowmeters use a drag-producing body in the flow stream to generate a force proportional to velocity. This force is sensed using strain gauges or a force balance system. The basic equation governing operation is that for the drag of a body in a flow stream and is similar to the equation for differential pressure flowmeters:

$$F = C_D A \frac{\rho V^2}{2g}$$

where F is the drag force; C_D is the drag coefficient; A is the frontal area of the body; ρ is the fluid density; V is the upstream fluid velocity; and g is the gravitational constant. In general the target, commonly a circular disk, is mounted on the pipe centerline to form an annular orifice. For pipe Reynolds numbers above 4000, the drag coefficient of such a design is essentially constant. At lower Reynolds numbers the drag and meter coefficient depend on the d/D ratio and operating Reynolds numbers. The target meter has greatest application in the measurement of hot, viscous, or sediment-bearing fluids that would plug or congeal in the pressure taps of a differential-pressure meter. Accuracy is typically 2% of full-scale flow and turndown 5:1.

5.3. Variable-Area Flowmeters. In variable-head flowmeters, the pressure differential varies withflow rate across a constant restriction. In variable-area meters, the differential is maintained constant and the restriction area allowed to change in proportion to the flow rate. A variable-area meter is thus essentially a form of variable orifice. In its most common form, a variable-area meter consists of a tapered tube mounted vertically and containing a float that is free to move in the tube. When flow is introduced into the small diameter bottom end, the float rises to a point of dynamic equilibrium at which the pressure differential across the float balances the weight of the float less its buoyancy. The shape and weight of the float, the relative diameters of tube and float, and the variation of the tube diameter with elevation all determine the performance characteristics of the meter for a specific set of fluid conditions. A ball float in a conical constant-taper glass tube is the most common design; it is widely used in the measurement of low flow rates at essentially constant viscosity. The flow rate is normally determined visually by float position relative to an etched scale on the side of the tube. Such a meter is simple and inexpensive but, with care in manufacture and calibration, can provide readings accurate to within several percent of full-scale flow for either liquid or gas.

A variety of other float shapes are available, some of which are designed to be insensitive to fluid viscosity changes. Tubes having various tapers are made to give linear or logarithmic scales and long slow taper tubes are available for higher resolution. Tubes may contain flutes, triangular flats, or guide rods to center the float and prevent chatter. Metal tubes are available for high pressure service. In these, a magnetic coupling typically detects the float position and an external indicator or transmitter is used to provide the flow reading. Other somewhat less common forms of the variable-area meter use a tapered plug riding vertically within the bore of an orifice. The area of the restriction is controlled to maintain the differential-pressure constant flow rate is proportional to the effective restriction area and is derived from the motion of the plug.

Because of the design, variable-area meters are relatively insensitive to the effects of upstream piping and have a pressure loss which is essentially constant over the whole flow range. These meters have greatest application where direct visual indication of relatively low flow rates of clean liquids or gases are required. Common applications are laboratory measurements, process purge flows, chemical analyzers, and medical gas dispensing. Variable-area meters can be readily fitted with high or low flow alarms. A common use for these meters is to provide a relatively low cost method of protecting critical equipment from lubrication failure.

5.4. Head-Area Meters. The Bernoulli principle, the basis of closed-pipe differential-pressure flow measurement, can also be applied to open-channel liquid flows. When an obstruction is placed in an open channel, the flowing liquid backs up and, by means of the Bernoulli equation, the flow rate can be shown to be proportional to the head, the exact relationship being a function of the obstruction shape.

Weirs. Weirs are dams or obstructions built across open channels that have, along their top edge, an opening of fixed dimensions and shape through which the stream can flow. This opening is called the weir notch and its bottom edge is designated the crest. Weirs are commonly used in irrigation, water works, wastewater discharge lines, electrical generating facilities, and pollution monitoring.

Predictable forms of weirs have been developed that are classified according to the shape of the notch. The discharge of each type can be determined from tables (8) or by actual flow calibration. Selection of weir type is dependent on the nature of the application. A broad-crested rectangular notch (Fig. 10**a**) allows streamline development to pass most floating debris and works at lower heads than a sharp-crested weir. Triangular, sharp-crested weirs (Fig. 10**d**) provide maximum flow range but do not transport floating material. The trapezoidal notch (Fig. 10**c**) is a combination of the rectangular and triangular forms. In the Cippoletti design, the slope of the ends has a value so that the additional discharge through the triangular portions of the notch exactly compensates for the effects of end contractions. Special forms of notches can be constructed to simplify the flow head relationship. Figure 10**f** shows one such form.

For accurate flow measurement the channel area upstream of the weir should be large enough to allow the flow to develop a smooth flow pattern and a velocity of 0.1 m/s or less. The downstream channel must be large enough to prevent high flow rates from submerging the weir and the flow over the notch must be sufficient for it to clear the downstream face as shown in Figures 10**b** and 10**e**. This free-discharge mode is the basis of weir capacity tables.

Flumes. Flumes, open channels that have gradual rather than sharp restrictions, are closely analogous to venturi meters for closed pipes. Weirs are analogous to orifice plates. The flume restriction may be produced by a contraction of the sidewalls, by a raised portion of the channel bed (a low broad-crested weir), or by both. One common design is the Parshall flume shown in Figure 11. Dimensions and capacity tables for Parshall flumes are available (9). Flumes,

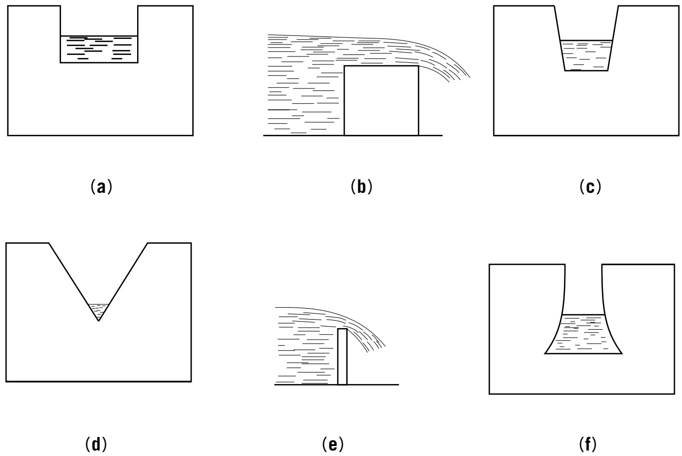


Fig. 10. Stream flow over (**a**) a broad-crested, rectangular weir; (**b**) a cross-current view of the rectangular and Cipolletti weirs; (**c**) a trapezoidal-notch or Cipolletti weir; (**d**) a sharp-crested, triangular, or V-notch weir; (**e**) a cross-current view of the V-notch and hyperbolic-notch weirs; and (**f**) a hyperbolic-notch weir.

widely used in measuring irrigation water, are alternatives to weirs where lower head requirements, higher capacity, and reduced sensitivity to silting are advantageous. Flumes are generally considered more expensive and less accurate than sharp-crested weirs.

A number of flume designs have been created specifically for use in partially filled circular conduits such as sewers. These are available in molded fiber glass

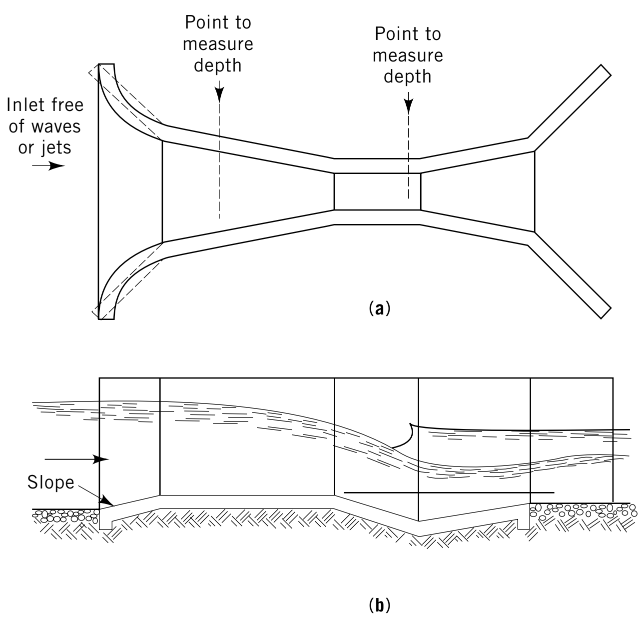


Fig. 11. The Parshall flume showing (**a**) flume construction and (**b**) stream flow (9).

and can be lowered through a manhole if required. As with all open-channel head-area meters, flumes must be sized to prevent submergence of the restriction.

5.5. Cup and Vane Anemometers. A number of flowmeter designs use a rotating element kept in motion by the kinetic energy of the flowing stream such that the speed is a measure of fluid velocity. In general, these meters, if used to measure wind velocity, are called anemometers; if used for open-channel liquids, current meters; and if used for closed pipes, turbine flowmeters.

Cup anemometers have shaped cups mounted on the spokes of a wheel. The cups, under the action of the fluid forces, spin in a horizontal plane about a vertical shaft mounted in bearings. Vane or propeller types use a multibladed rotor, the axis of which is parallel to the flow direction as the rotating member. Both designs are commonly used for wind speed measurement or similar applications such as the velocity in ventilation ducts. Because of inertia, anemometers are most accurate under steady conditions. Velocity fluctuations cause readings that are too high.

5.6. Current Meters. Various vane designs have been adapted for open-channel flow measurement. The rotating element is partially immersed and rotates rather like a water wheel. Operation is similar to that of vane anemometers.

5.7. Turbine Meters. The turbine meter represents a refinement of the anemometer or current-meter design for use in a closed conduit. A typical turbine cross section is shown in Figure 12. Flow entering the meter is directed through a flow-straightening section that shapes the flow and acts as a rotor support. The flow then turns the helically bladed rotor and passes through a rear-support section. A magnetic pick-off coil, or other externally mounted proximity detector, senses the passage of the rotor blade. At a steady velocity the rotor comes to a speed at which the angle of the fluid striking the blade produces a driving force that is just sufficient to balance the drag forces resisting rotation. This angle of attack is a measure of the total forces on the rotor resisting rotation. For maximum range, it is essential that these drag forces and the attack angle are as small as possible.

The output of turbine meters is inherently digital, provides a high information rate, and has excellent accuracy and repeatability over a wide range. Turbines are available in sizes from 6 to 600 mm. Typical accuracy is ±0.5% of

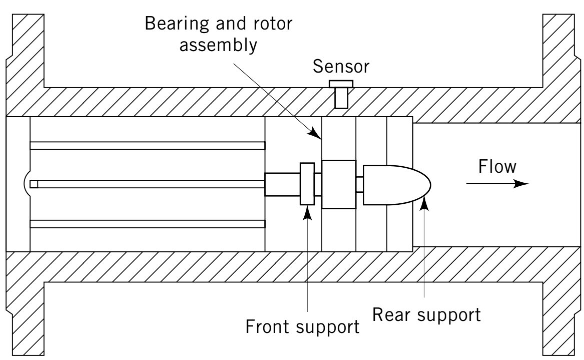


Fig. 12. Turbine meter cross-section.

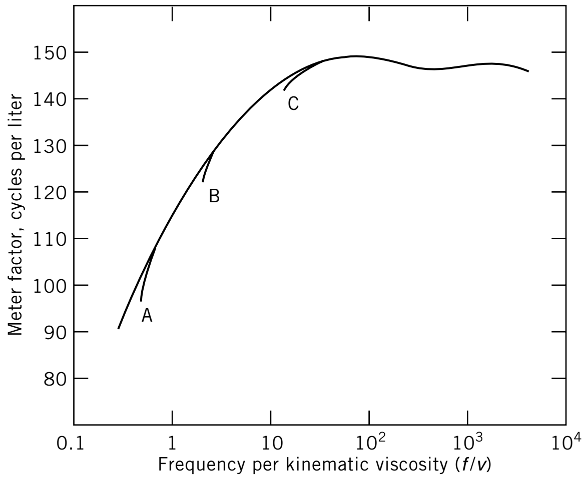


Fig. 13. A turbine flowmeter composite-calibration curve. For viscosities of A, 50 mm^2/s; B, 10 mm^2/s; C, 1 mm^2/s, where 1 $mm^2/s = 1$ cSt.

reading over flow ranges of 10:1 or greater in large sizes. In smaller sizes friction and viscosity effects reduce the linear range. Lower cost meters having reduced accuracy specifications are also available.

A typical universal viscosity performance curve is shown in Figure 13, where meter output is plotted against operating frequency divided by kinematic viscosity, which is analogous to Reynolds number. Calibration at four different viscosities all overlay down to some lowflow rate where either mechanical or magnetic drag forces, or both, become significant. This point defines the lower limit of the predictable-performance range. Because of excellent curve repeatability, the output can be made linear to low Reynolds numbers using microprocessor-based programmable secondaries.

Turbine meters designed for clean liquids use ball bearing mounted rotors for low friction and wide range. Typical uses include aerospace and aircraft testing, cryogenic liquid measurement (see CRYOGENIC TECHNOLOGY), and the digital blending of petroleum products. Models are also available using self-cleaning journal bearings that provide a shorter measurement range but superior service life in the presence of fluid contamination. These meters are used in a broad range of industrial environments including liquids, gases, and steam.

5.8. Oscillatory Flowmeters. Three different oscillatory fluid phenomena are used in flow measurement.

Fluid Oscillation. Fluidic flowmeters are based on wall attachment, ie, the Coanda effect, and the technology of bistable fluid oscillators such as those used in fluid logic. A fluidic meter (Fig. 14**a**) consists of an entrance nozzle section and a diverging section where the walls are designed to permit the flow to attach to one side or the other, but not to both. Downstream feedback passages connect with control ports upstream of the point of attachment. In operation, natural turbulence and the Coanda effect cause the flow jet to attach to one side wall. As the flow is biased to this side, a portion of it is directed through the feedback passage

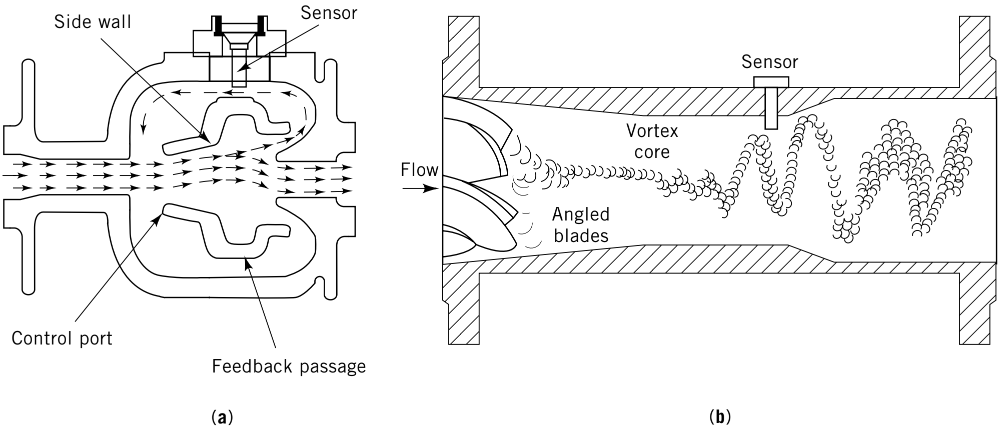


Fig. 14. Cross sections of oscillatory flow meters: (**a**) fluidic, where (→) represents the main flow and (→- →) the feedback, and (**b**) vortex precession.

to the control port causing the jet to switch to the opposite side where the same feedback action is repeated. The result is a continuous oscillation having a frequency linearly related to the fluid velocity. This frequency is detected by means of a sensor in one of the feedback passages (see SENSORS). Fluidic flowmeters have been applied to the measurement of clean, low viscosity liquids in pipe sizes 80 mm and smaller, but have never achieved wide acceptance.

Vortex Precession. When a swirling body of fluid enters a divergent section of the center of rotation precesses, ie, it leaves a straight line and takes up a helical path. Using a meter based on this principle (Fig. 14b), entering fluid is given a rotational component of velocity by a set of fixed blades creating a rotational fluid profile, the centerline of which coincides with the meter centerline. This flow profile is stabilized and accelerated by a convergent section before it enters an enlarged section that causes precession to take place. The frequency of this precession, detected by a dynamic pressure sensor, is linear with volumetricflow rate over a wide range. Typical accuracy is ±1% of actual flow.

Vortex precession meters feature no moving parts and a relatively high frequency digital output. They are used in the measurement of gas and liquid flows, generally in pipe sizes 80 mm and smaller.

Vortex Shedding. When a streamlined body is placed in a flowing stream, the fluid follows the contours of the body without separating from its surface. If, however, the body is bluff or nonstreamlined, the fluid separates at some point from the surface and rolls into a vortex. For two-dimensional symmetrical bodies, the changes in local velocity and pressure associated with the separation on one side interact with vortex formation on the opposite side. This feedback quickly causes a stable pattern of alternate vortex shedding so that the downstream wake becomes a staggered pattern of vortices commonly referred to as a Karmen-vortex street. This pattern is shown for a cylindrical obstruction in Figure 15. It is this phenomena that causes the flapping of flags and the clear turbulence behind jet aircraft.

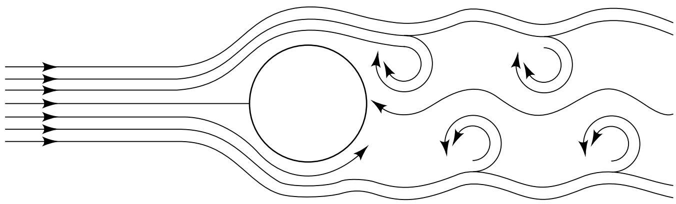


Fig. 15. Karmen-vortex pattern behind a circular cylinder.

The frequency of vortex formation is a linear function of the fluid velocity and the width of the obstruction at the point where shedding occurs. Vortex-shedding flowmeters use various forms of well-defined symmetrical obstructions to optimize vortex formation and detect the vortices using sensors which respond to local velocity or pressure changes. Since these meters originally became available in the early 1970s, improved sensors have broadened the application range of the vortex-shedding meter. Vortex-sensing techniques include differential-pressure-sensing diaphragms (having capacitive or inductive pick-off), strain gauges, piezoelectric crystals, and thermistors.

Vortex-shedding flowmeters typically provide 1% offlow rate accuracy over wide ranges on liquid, gas, and steam service. Sizes are available from 25 to 200 mm. The advantages of no moving parts and linear digital output have resulted in wide usage in the measurement of steam, water, and other low viscosity liquids.

6. External Stimulus Flowmeters

External stimulus flowmeters are generally electrical in nature. They derive their signal from the interaction of the fluid motion with some external stimulus such as a magnetic field, laser energy, an ultrasonic beam, or a radioactive tracer.

7. Electromagnetic Flowmeters

Faraday's law of electromagnetic induction states that relative motion, at right angles, between a conductor and a magnetic field induces a voltage in the conductor. The magnitude of the induced voltage is proportional to the relative velocity of the conductor and the magnitude of the magnetic field. This principle is used to measure the flow of conducting liquids using meter designs similar to that of Figure 16. A pair of coils produces an electromagnetic field through an insulating tube carrying the liquid. Electrodes at a right angle to both the flow and field sense the induced voltage, E:

$$E = CBdV$$

where C is the meter calibration factor; B is the average magnetic flux density; d is the distance between electrodes; and V is the average fluid velocity.

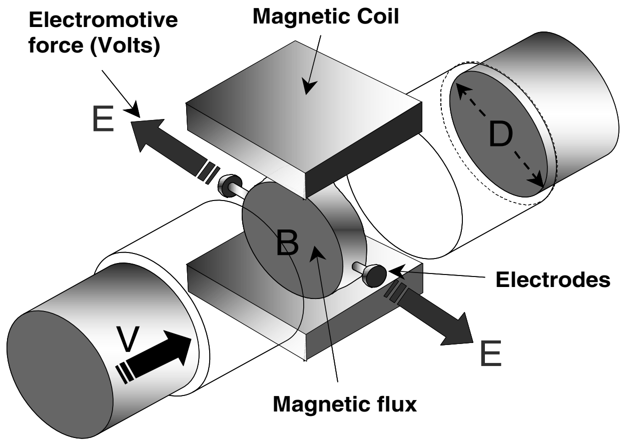


Fig. 16. Electromagnetic flow meter.

Electromagnetic flowmeters are available using either alternating current (ac) or pulsed direct current (dc) coil drives. The ac-actuated meters require zero adjustment at full pipe and no flow conditions. These meters provide a high accuracy and wide turndown and are the preferred meter in certain applications. The main limitation on performance is a tendency to zero shift in coating applications. Electromagnetic flowmeters that use a pulsed dc voltage coil excitation, eliminate the zero shift problem. These meters use a duty cycle where the signal M_1 is measured during steady-state conditions ($d\theta/dt = 0$) with the field coils on, and M_2 is similarly measured with the coil off. The on–off period is synchronized at a multiple of the line frequency so any ac power noise averages out. The difference $M_1 - M_2$ is thus directly proportional to the flow. Meters of this design function accurately under conditions where sinusoidal excitation meters do not provide acceptable results. Because of their design, pulsed dc meters have a slower speed of response than ac excitation types.

The exact magnitude of the generated voltage of an electromagnetic flowmeter is an integration of the individual velocity and field vectors along the three-dimensional path between the electrodes. Modern designs use characterized fields to weigh all velocities equally. In this manner, the meter is made less sensitive to changes in velocity profile than other common meters.

Electromagnetic flowmeters are available with various liner and electrode materials. Liner and electrode selection is governed by the corrosion characteristics of the liquid. For corrosive chemicals, fluoropolymer or ceramic liners and noble metal electrodes are commonly used. Polyurethane or rubber and stainless steel electrodes are often used for abrasive slurries. Some fluids tend to form an insulating coating on the electrodes introducing errors or loss of signal. To overcome this problem, specially shaped electrodes are available that extend into the flow stream and tend to self-clean. In another approach, the electrodes are periodically vibrated at ultrasonic frequencies.

Another approach to the problem of electrode coating is the electrodeless magnetic flowmeter. In this design there are no electrodes in contact with the process. Large plates placed on the outside of a ceramic spool perform the same function and are capacitively coupled to the transmitter through a high impedance amplifier. This meter has been found to provide satisfactory service at very low fluid conductivities and under coating conditions where other magnetic flowmeters required cleaning after short periods of operation.

Additional magnetic flowmeter innovations have been the addition of low flow and empty pipe cutoffs. The low flow cutoff is normally set to a value of from 1 to 5% of range setting and drops the output signal to zero when theflow rate reaches this level. This feature is useful in preventing erroneous signals owing to sloshing when there is no net flow. Many piping systems allow the magnetic flowmeter to drain empty when flow stops. When this occurs the meter has an unstable output. To prevent errors under this condition some magnetic flowmeters contain a pair of contacts that drive the signal to zero when actuated by a dry contact closure. Contact closure is provided from a pump or valve as appropriate.

Electromagnetic flowmeters are available in essentially all pipe sizes, ie, <1 mm to >3 m, and provide measurement accuracy of 1% of rate or better over wide ranges. The meters are obstructionless, have no moving parts, and are extremely rugged. Pressure loss is that of an equivalent section of pipe. The meters are insensitive to viscosity, density, and temperature changes. Fluid conductivity has no effect on meter performance provided it is above a minimum level which is a function of meter design. Models having thresholds as low as 2 μS/cm (tap water typically has a value of 500 μS/cm) are available. Electromagnetic flowmeters have the additional advantage of sensing flows containing entrained gas or solids on a flowing volume basis provided the flow is well mixed and traveling at a common overall velocity.

Because of these characteristics electromagnetic flowmeters have been widely applied to the measurement of difficult liquids such as raw sewage and wastewater flows, paper pulp slurries, viscous polymer solutions, mining slurries, milk, and pharmaceuticals. They are also used in less demanding applications such as the measurement of large domestic water volumes.

Several special forms of electromagnetic flowmeters have been developed. A dc field version is used for liquid metals such as sodium or mercury. Pitot and probe versions provide low cost measurements within large conduits. Another design combines a level sensor and an electromagnetic meter to provide an indication of flow within partially full conduits such as sewer lines.

7.1. Momentum Flowmeters. Momentum flowmeters operate by superimposing on a normal fluid motion a perpendicular velocity vector of known magnitude thus changing the fluid momentum. The force required to balance this change in momentum can be shown to be proportional to the fluid density and velocity, the mass-flow rate.

7.2. Coriolis-Type Flowmeters. In Coriolis-type flowmeters the fluid passes through a flow tube being electromechanically vibrated at its natural frequency. The fluid is first accelerated as it moves toward the point of peak vibration amplitude and is then decelerated as it moves from the point of peak amplitude. This creates a force on the inlet side of the tube in resistance to the acceleration and an opposite force on the outlet side resisting the deceleration. The result of these forces is an angular deflection or twisting of the flow tube

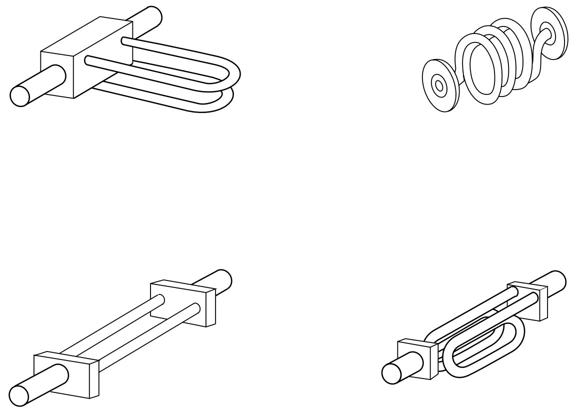


Fig. 17. Coriolis flowmeter tube configurations.

that is directly proportional to the mass flow rate through the tube.This inherent mass capability is a prime advantage of this technology over most other flowmeters.

A number of meter designs have been developed based on this principle. Some are shown in Figure 17. Certain advantages are claimed for each, but all share a number of characteristics. Perhaps the most important property is a full-scale deflection on the order of 0.001 mm. The sensors for these meters are extremely sensitive, stable, and capable of being temperature compensated.

Coriolis flowmeters are available in line sizes from 0.1 to 200 mm and are sensitive enough to measure liquid flow rates in grams per hour. Typical rangeability is 25:1 with accuracies reaching ±0.25% of actual flow rate. Installation procedures vary although rigid pipe supports just beyond the meter ends are normally recommended. A downstream shutoff valve is also desirable to enable in-place zero adjustment. In some systems, such as those using positive displacement pumps, a bypass line may be required to relieve shutoff pressure during zeroing.

Coriolis meters were first developed in the 1970s and continue to increase their range of application. These meters are being applied in many areas that were previously metered by other flowmeter technologies. The greatest application has been in food and chemical processing.

Axial-Flow Angular-Momentum Flowmeter. In this design, an impeller is rotated at constant speed in the flow field imparting a constant angular momentum to it. A downstream rotor absorbs this momentum but is restrained from rotating. Using Newton's second law, the torque generated by the change in momentum is

$$T = WR^2M$$

where T is the fluid torque; W is the fluid angular velocity; R is the radius of gyration of the fluid; and M is the mass-flow rate. If a balance torque is supplied by a closed-loop servosystem, the torque of which may be expressed by

$$T = KWV$$

where K is a controlled constant and V is a voltage signal to the servo, then

$$V = \frac{R^2 M}{K}$$

The servovoltage is a function of mass-flow rate. Axial-flow angular-momentum meters are sometimes used in measuring jet engine fuel flow as the fuel energy content correlates much more closely with mass than volume.

7.3. Ultrasonic Flowmeters. Ultrasonic flowmeters can be divided into three broad groups: passive or turbulent noise flowmeters, Doppler or frequency-shift flowmeters, and transit time flowmeters.

Passive Detectors. Passive or turbulent noise detectors are ultrasonic microphones clamped on to the flow conduit. These microphones respond to some portion of the frequency spectrum of turbulent noise within the pipe. This noise increases with increasing velocity although the exact relationship is dependent on the particular installation. Passive detectors can be used for liquids, gases, or slurries to activate flow switches or to provide a low cost general indication of relative flow. Because this signal is generated by the flow itself, passive detectors are actually self-generating flowmeters. Other types, the great majority of ultrasonic flowmeters, are not self-generating.

Doppler Flowmeters. Doppler flowmeters sense the shift in apparent frequency of an ultrasonic beam as it is reflected from air bubbles or other acoustically reflective particles that are moving in a liquid flow. It is essential for operation that at least some particles are present, but the concentration can be low and the particles as small as ~40 μm. Calibration tends to be influenced by particle concentration because higher concentrations result in more reflections taking place near the wall, in the low velocity portion of the flow profile. One method used to minimize this effect is to have separate transmitting and receiving transducers focused to receive reflections from an intercept zone near the center of the pipe.

Both wetted-sensor and clamp-on Doppler meters are available for liquid service. A straight run of piping upstream of the meter and a Reynolds number of >10,000 are generally recommended to ensure a well-developed flow profile. Doppler meters are primarily used where stringent accuracy and repeatability are not required. Slurry service is an important application area.

Transit Time Flowmeters. This type of ultrasonic meter depends on measuring the transit time of an ultrasonic beam through the flow. In most designs, a pair of ultrasonic transducers are mounted diagonally on opposite sides of a pipe section. These transducers may be wetted, ie, built into the flowmeter, or clamped onto the outside of an existing pipe. In one design these transducers simultaneously transmit upstream and downstream ultrasonic pulses and measure the transit time until the leading edge of the pulse is received at the opposite transducer. The transit time for the pulse moving in the direction of the flow is less than for the pulse moving against the flow. Transit times are given by the expressions:

$$t_u = \frac{L}{C + V_1} \; t_d = \frac{L}{C - V_1}$$

where t_u is the transit time in the upstream direction; t_d is the transit time in the downstream direction; L is the acoustic path length; C is the speed of sound in the fluid; and V_1 is the average component of liquid velocity V along the acoustic path. The difference in transit times, $t_d - t_u = \Delta t$, is

$$\Delta t = \frac{2LV_1}{C^2 - V_1^2}$$

Because $C^2 \gg V^2$ and $V_1 = V \cos \theta$,

$$\Delta t = \frac{2LV\cos\theta}{C^2}$$

or

$$V = C^2 \frac{\Delta t}{2L\cos\theta}$$

The flow velocity is thus proportional to the difference in transit time between the upstream and downstream directions and to the square of the speed of sound in the fluid. Because sonic velocity varies with fluid properties, some designs derive compensation signals from the sum of the transit times which can also be shown to be proportional to C.

The angle θ can also change owing to changes in the refraction angle in accordance with Snell's law. This is primarily a problem in clamp-on designs where the pipe wall material is not controlled. Thermal gradients in the fluid may also cause problems by distorting the acoustic path. Designs that use a single acoustical path are inherently sensitive to velocity profile and swirl. These require good upstream piping and fully turbulent flow to provide accurate measurement. Multiple path designs are also available. These provide greater precision where well-controlled conditions cannot be maintained. The relatively long transit path of large pipes also permits operation at lower velocities than is possible in small pipes. Greatest application has been on liquid service in large pipes where flow profile and fluid properties are relatively constant, although gas designs are now available.

A variation on the transit time method is the frequency-difference or sing-around method. In this technique, pulses are transmitted between two pairs of diagonally mounted transducers. The receipt of a pulse is used to trigger the next pulse. Alternatively, this can be done using one pair of transducers where each acts alternately as transmitter and receiver. The frequency of pulses in each loop is given by

$$f_u = \frac{1}{t_u} \quad f_d = \frac{1}{t_d}$$

where f_u is the frequency of pulses in the upstream loop and f_d is the frequency of pulses in the downstream loop.

$$\Delta f = f_u - f_d = \frac{(C + V_1)}{L} - \frac{(C - V_1)}{L} = \frac{2V_1}{L} = \frac{2V\cos\theta}{L}$$

so that

$$V = \frac{L\,\Delta f}{\cos\theta}$$

The flow velocity in this design is therefore proportional to the difference between the frequencies but independent of sonic speed within the fluid.

In practice Δf is a small number and the sing-around frequencies are scaled up for display. In one example, for a pipe 1 m in diameter and water flowing at 2 m/s, the frequency difference is 1.4 Hz (10). Frequency difference transit time meters provide greater resolution than normal transit time ultrasonic meters. The greatest application is in sizes from 100-mm to 1-m diameter.

Transit time ultrasonic flowmeters require a homogeneous fluid without a high density of reflective particles; in this sense fluid requirements are opposite those of a Doppler-type although there is an area of overlap. These flowmeters have the advantages of being obstructionless with low pressure drop, having a wide range, and being bidirectional. The accuracy capability depends on the technique selected and the control of flow profile and fluid properties. Typical specifications range from $\pm 5\%$ of full scale to $\pm 1\%$ of actualflow rate.

Smart designs using microprocessor-based electronics are available using clamp on nonwetted transducers in both Doppler and transit time designs. These meters are convenient for making flow measurements on existing pipes. The pipe material and thickness, as well as any liner material and thickness, are programmed in the unit to permit flow area and sonic velocity corrections. These meters can be repeatable to 0.5% of full-scale flow. Absolute accuracy is dependent on application and installation parameters. Sound absorbing liners such as cement or glass may affect the measurement.

7.4. Laser Doppler Velocimeters. Laser Doppler flowmeters have been developed to measure liquid or gas velocities in both open and closed conduits. Velocity is measured by detecting the frequency shift in the light scattered by natural or added contaminant particles in the flow. Operation is conceptually analogous to the Doppler ultrasonic meters. Laser Doppler meters can be applied to very low flows and have the advantage of sensing at a distance, without mechanical contact or interaction. The technique has greatest application in open-flow studies such as the determination of engine exhaust velocities and ship wake characteristics.

7.5. Correlation Flowmeters. *Tracer Type.* A discrete quantity of a foreign substance is injected momentarily into the flow stream and the time interval for this substance to reach a detection point, or pass between detection points, is measured. From this time, the average velocity can be computed. Among the tracers that have historically been used are salt, anhydrous ammonia, nitrous oxide, dyes, and radioactive isotopes. The most common application area for tracer methods is in gas pipelines where tracers are used to check existing metered sections and to spot-check unmetered sections.

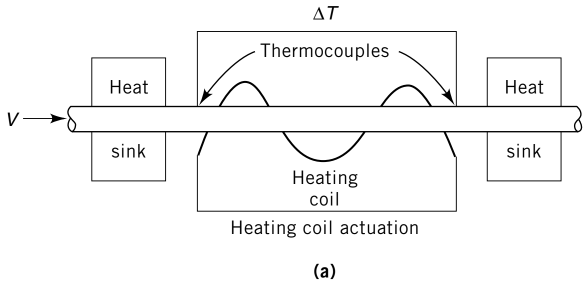
Cross Correlation. Considerable research has been devoted to correlation techniques where a tracer is not used. In these methods, some characteristic pattern in the flow, either natural or induced, is computer-identified at some point or plane in the flow. It is detected again at a measurable time later at a position slightly downstream. The correlation signal can be electrical, optical, or acoustical. This technique is used commercially to measure paper pulp flow and pneumatically conveyed solids.

7.6. Thermal Flowmeters. *Hot-Wire and Hot-Film Anemometers.* Hot-wire devices depend on the removal of heat from a heated wire or film sensor exposed to the fluid velocity. The sensor is typically connected in a bridge circuit with a similar sensor that is not exposed to the velocity in the opposite leg of the bridge. This provides compensation for fluid temperature changes. Hot-wire anemometers are normally operated in a constant temperature mode. The resistance of the sensor, and therefore its temperature, is maintained constant at a value slightly over the fluid temperature by a servo-amplifier. In this mode, the current to the sensor becomes the flow-dependent variable. Constant temperature operation minimizes thermal inertia and makes the system capable of sensing rapid changes in velocity. Hot-wire signals are dependent on the heat transfer from the sensor and thus on both the fluid velocity and density, ie, the mass-flow rate. These signals are also dependent on the thermal conductivity and specific heat of the fluid and are susceptible to any contamination that changes the heat transfer. For these reasons hot-wire and hot-film anemometers are primarily used in clean liquids and gases where they can be calibrated for the exact condition of use. Applications are in the measurement of low air velocities both in the atmosphere and in building ventilation studies.

Differential-Temperature Thermal Flowmeters. Meters of this type inject heat into the fluid and measure the resulting temperature rise or, alternatively, the amount of power required to maintain a constant temperature differential. The power required to raise the temperature of a flowing stream by an amount ΔT is given by the relation:

$$P = MC_p\Delta T$$

where M is the mass-flow rate; P is the required power; C_p is the specific heat at constant pressure, and ΔT is the temperature rise. The thermal meter can therefore measure the mass-flo rate of a particular gas independent of pressure provided the specific heat is constant, a condition that is approximately true for most changes in temperature or pressure. The original differential temperature design heated the entire stream via a grid network and measured the temperature upstream and downstream with resistance grids. Because of high power consumption this design has been supplanted by several forms that retain the essential features, but provide lower power consumption and better corrosion protection. In one form, the outside of the meter tube is symmetrically heated by an external coil. Thermocouples are located on the tube wall equidistant from ends of the tube (Fig. 18). Heat sinks placed at the ends of the tube cause a symmetrical temperature pattern at zero flow and no temperature differential is measured between thermocouples. When fluid flows through the tube, the temperature distribution becomes skewed in the downstream direction and a differential is generated between the thermocouples which is dependent on the mass flow. Small differential temperature thermal meters are used to meter corrosive gases such as chlorine.



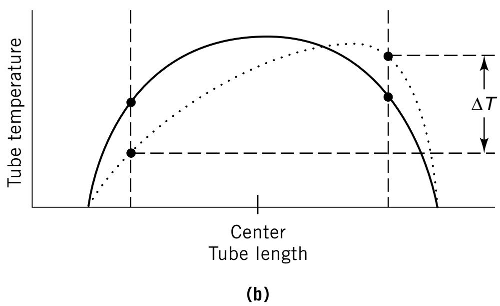


Fig. 18. (**a**) Differential-temperature thermal flowmeter. (**b**) Tube length–temperature profiles for (—) zero flow and (· · ·) flow. ΔT is the temperature differential measured by the thermocouples.

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