CHAPTER 9

Flow

9.1 Introduction

The accurate measurement of fluid flow is very important in many industrial applications. Optimum performance of many processes requires specific flow rates. The cost of many liquids and gases are based on the measured flow through a pipeline, making it necessary for accounting purposes to accurately measure and control the rate of flow. This chapter discusses the basic terms, formulas, and techniques used in flow measurements and flow instrumentation. Highly accurate and rugged flow devices have now been developed and are commercially available. Developments in technology are continually improving measurement devices [1, 2]. However, one single flow device is not suitable for all applications, and careful selection is required.

9.2 Fluid Flow

At low flow rates, fluids have a laminar flow characteristic. As the flow rate increases, the laminar flow starts to break up and becomes turbulent. The speed of the liquid in a fluid flow varies across the flow. Where the fluid is in contact with the constraining walls (the boundary layer), the velocity of the liquid particles is virtually zero, while in the center of the flow, the liquid particles have the maximum velocity. Thus, the average rate of flow is used in flow calculations. The units of velocity are normally feet per second (ft/s), or meters per second (m/s). In a liquid, the fluid particles tend to move smoothly in layers with laminar flow, as shown in Figure 9.1(a). The velocity of the particles across the liquid takes a parabolic shape. With turbulent flow, the particles no longer flow smoothly in layers, and turbulence, or a rolling effect, occurs. This is shown in Figure 9.1(b). Note also the flattening of the velocity profile.

9.2.1 Flow Patterns

Flow can be considered to be laminar, turbulent, or a combination of both. Osborne Reynolds observed in 1880 that the flow pattern could be predicted from physical properties of the liquid. If the Reynolds number(R) for the flow in a pipe is equal to or less than 2,000, the flow will be laminar. If the Reynolds number ranges from 2,000 to approximately 5,000, this is the intermediate region, where the flow can be laminar, turbulent, or a mixture of both, depending upon other factors. Beyond

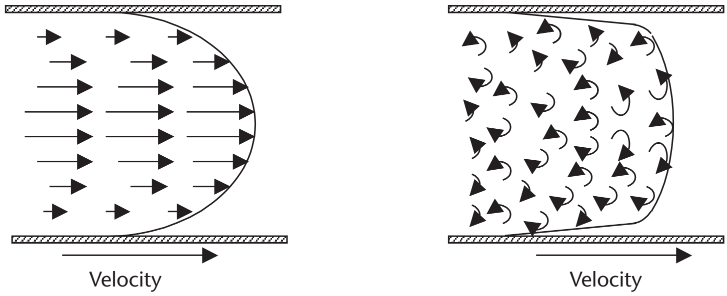

Figure 9.1 Flow velocity variations across a pipe with (a) laminar flow, and (b) turbulent flow.

approximately 5,000, the flow is always turbulent. The Reynolds number is a derived dimensionless relationship, combining the density and viscosity of a liquid with its velocity of flow and the cross-sectional dimensions of the flow, and takes the form:

$$R = \frac{VD\rho}{\mu} \tag{9.1}$$

where V is the average fluid velocity, D is the diameter of the pipe, ρ is the density of the liquid, and μ is the absolute viscosity.

Dynamic or absolute viscosity is used in the Reynolds flow equation. Table 9.1 gives a list of viscosity conversions. Typically, the viscosity of a liquid decreases as temperature increases.

Example 9.1

What is the Reynolds number for glycerin flowing at 7.5 ft/s in a 17-in diameter pipe? The viscosity of glycerin is 18×10^{-3} lb s/ft^2 and the density is 2.44 lb/ft^3.

$$R = \frac{7.5 \times 17 \times 2.44}{12 \times 18 \times 10^{-3}} = 1{,}440$$

Flow rate is the volume of fluid passing a given point in a given amount of time, and is typically measured in gallons per minute (gal/min), cubic feet per minute (ft^3/min), liters per minute (L/min), and so forth. Table 9.2 gives the flow rate conversion factors.

In a liquid flow, the pressures can be divided into the following: (1) static pressure, which is the pressure of fluids or gases that are stationary (see point A in

Table 9.1 Conversion Factors for Dynamic and Kinematic Viscosities

Dynamic Viscosities	*Kinematic Viscosities*
1 lb s/ft^2 = 47.9 Pa s	1ft^2/s = 9.29×10^{-2} m^2/s
1 centipoise = 10 Pa s	1 stoke = 10^{-4} m^2/s
1 centipoise = 2.09×10^{-5} lb s/ft^2	1 m^2/s = 10.76 ft^2/s
1 poise = 100 centipoise	1 stoke = 1.076×10^{-3} ft^2/s

Table 9.2 Flow Rate Conversion Factors

1 gal/min = 6.309 × 10^{-5} m^3/s	1 L/min = 16.67 × 10^{-6} m^3/s
1 gal/min = 3.78 L/min	1 ft^3/s = 449 gal/min
1 gal/min = 0.1337 ft^3/min	1 gal/min = 0.00223 ft^3/s
1 gal water = 231 in^3	1 ft^3 water = 7.48 gal
1 gal water = 0.1337 ft^3 = 231 in^3, 1 gal water = 8.35 lb,	
1 ft^3 water = 7.48 gal, 1,000 L water = 1 m^3, 1 L water = 1 kg	

Figure 9.2); (2) dynamic pressure, which is the pressure exerted by a fluid or gas when it impacts on a surface (point B – A); and (3) impact pressure (total pressure), which is the sum of the static and dynamic pressures on a surface, as shown by point B in Figure 9.2.

9.2.2 Continuity Equation

The continuity equation states that if the overall flow rate in a system is not changing with time [see Figure 9.3 (a)], then the flow rate in any part of the system is constant. From which:

$$Q = VA \tag{9.2}$$

where Q is the flow rate, V is the average velocity, and A is the cross-sectional area of the pipe. The units on both sides of the equation must be compatible (i.e., English units or metric units).

Example 9.2

What is the flow rate in liters per second through a pipe 32 cm in diameter, if the average velocity is 2.1 m/s?

$$Q = \frac{2.1 m/s \times \pi \times 0.32^2\ m^2}{4} = 0.17 m^3/s = 0.17 \times 1{,}000 L/s = 170 L/s$$

If liquids are flowing in a tube with different cross-sectional areas, such as A_1 and A_2, as shown in Figure 9.3(b), then the continuity equation gives:

$$Q = V_1A_1 = V_2A_2 \tag{9.3}$$

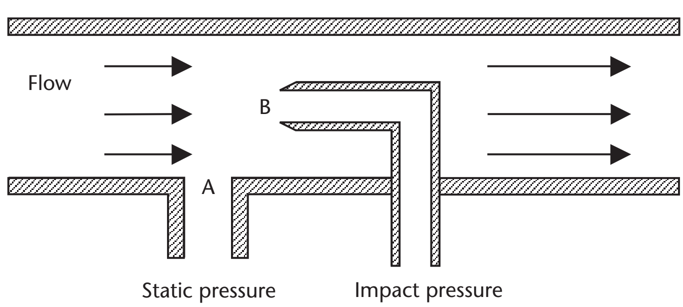

Figure 9.2 Static, dynamic, and impact pressures.

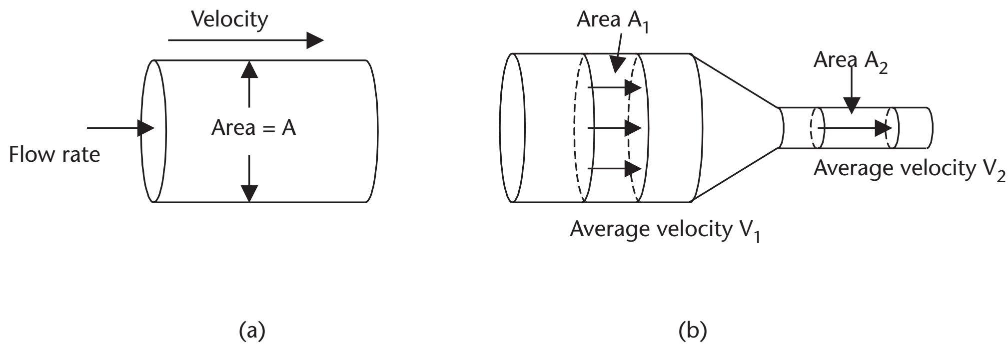

Figure 9.3 Flow diagram for use in the continuity equation with (a) constant area, and (b) differential areas.

Example 9.3

If a pipe changes from a diameter of 17 to 11 cm, and the velocity in the 17cm section is 5.4 m/s, what is the average velocity in the 11cm section?

$$Q = V_1A_1 = V_2A_2$$

$$V_2 = \frac{5.4m^3/s \times \pi \times 8.5^2}{\pi \times 5.5^2\ m^2} = 12.8\,m/s$$

Mass flow rate (F) is related to volume flow rate (Q) by:

$$F = \rho Q \tag{9.4}$$

where F is the mass of liquid flowing, and ρ is the density of the liquid.

Since a gas is compressible, (9.3) must be modified for gas flow to:

$$\gamma_1 V_1 A_1 = \gamma_2 V_2 A_2 \tag{9.5}$$

where γ_1 and γ_2 are specific weights of the gas in the two sections of pipe.

Equation 9.3 is the rate of mass flow in the case of a gas. However, this could also apply to liquid flow, by multiplying both sides of the (9.3) by the specific weight (γ), to give the following:

$$\gamma V_1 A_1 = \gamma V_2 A_2 \tag{9.6}$$

9.2.3 Bernoulli Equation

The Bernoulli equation (1738) gives the relation between pressure, fluid velocity, and elevation in a flow system. When applied to Figure 9.4(a), the following is obtained:

$$\frac{P_A}{\gamma_A} + \frac{V_A{}^2}{2g} + Z_A = \frac{P_B}{\gamma_B} + \frac{V_B^2}{2g} + Z_B \tag{9.7}$$

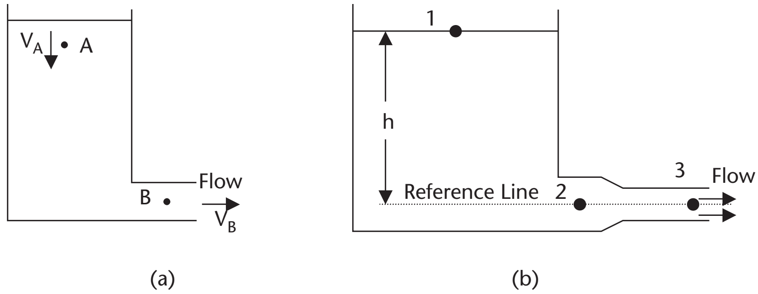

Figure 9.4 Container diagrams: (a) the pressures at points A and B are related by the Bernoulli equation, and (b) application of the Bernoulli equation to determine flow.

where P_A and P_B are absolute static pressures at points A and B, γ_A and γ_B are specific weights, V_A and V_B are average fluid velocities, g is the acceleration of gravity, and Z_A and Z_B are elevations above a given reference level (e.g., $Z_A - Z_B$ is the head of fluid).

The units in (9.6) are consistent, and reduce to units of length as follows:

$$\text{Pressure Energy} = \frac{P}{\gamma} = \frac{lb/ft^2\left(\text{N}/m^2\right)}{lb/ft^2\left(\text{N}/m^3\right)} = ft(m)$$

$$\text{Kinetic Energy} = \frac{V^2}{\gamma} = \frac{(ft/s)^2\,(m/s)^2}{ft/s^2\left(m/s^2\right)}\,ft(m)$$

$$\text{Potential Energy} = Z = ft(m)$$

This equation is a conservation of energy equation, and assumes no loss of energy between points A and B. The first term represents energy stored due to pressure; the second term represents kinetic energy, or energy due to motion; and the third term represents potential energy, or energy due to height. This energy relationship can be seen if each term is multiplied by mass per unit volume, which cancels, since the mass per unit volume is the same at points A and B. The equation can be used between any two positions in a flow system. The pressures used in the Bernoulli equation must be absolute pressures.

In the fluid system shown in Figure 9.4(b), the flow velocity V at point 3 can be derived from (9.7), and is as follows, using point 2 as the reference line:

$$\frac{P_1}{\gamma_1} + 0 + h = \frac{P_3}{\gamma_3} + \frac{V_3^2}{2g} + 0$$

$$V_3 = \sqrt{(2gh)} \qquad (9.8)$$

Point 3 at the exit has dynamic pressure, but no static pressure above 1 atm. Hence, $P_3 = P_1 = 1$ atm, and $\gamma_1 = \gamma_3$. This shows that the velocity of the liquid flowing out of the system is directly proportional to the square root of the height of the liquid above the reference point.

Example 9.4

If the height of a column of water h in Figure 9.3(b) is 4.3m, what is the pressure at P_2? Assume the areas at points 2 and 3 are 29 cm^2 and 17 cm^2, respectively?

$$V_3 = \sqrt{(2 \times 9.8 \times 4.3)} = 9.18 m/s$$

Considering points 2 and 3 with the use of (9.7):

$$\frac{P_2}{9.8kN} + \frac{V_2^2}{2 \times 9.8} + 0 = \frac{101.3kPa}{9.8kN} + \frac{V_3^2}{2 \times 9.8} + 0 \quad (9.9)$$

Using (9.3) and knowing that the areas at point 2 and 3 are 0.0029 m^2 and 0.0017 m^2, respectively, the velocity at point 2 is given by:

$$V_2 = \left(\frac{A_3}{A_2}\right) V_3 = \left(\frac{0.0017}{0.0029}\right) 9.12 m/s = 5.35 m/s$$

Substituting the values obtained for V_2 and V_3 into (9.8) gives the following:

$$\frac{P_2}{9.8} + \frac{(5.35)^2}{2 \times 9.8} + 0 = \frac{101.3}{9.8} + \frac{(9.12)^2}{2 \times 9.8} + 0$$

$$P_2 = 128.6 \text{ kPa(a)} = 27.3 \text{ kPa(g)}$$

9.2.4 Flow Losses

The Bernoulli equation does not take into account flow losses. These losses are accounted for by pressure losses, and fall into two categories: (1) those associated with viscosity and the friction between the constriction walls and the flowing fluid; and (2) those associated with fittings, such as valves, elbows, tees, and so forth.

The flow rate Q from the continuity equation for point 3 in Figure 9.3(b), for instance, gives:

$$Q = V_3 A_3$$

However, to account for the *outlet losses*, the equation should be modified to:

$$Q = C_D V_3 A_3 \quad (9.10)$$

where C_D is the discharge coefficient, which is dependent on the shape and size of the orifice. The discharge coefficients can be found in flow data handbooks.

Frictional losses are losses from the friction between the flowing liquid and the restraining walls of the container. These frictional losses are given by:

$$h_L = \frac{fLV^2}{2Dg} \quad (9.11)$$

where h_L is the head loss, f is the friction factor, L is the length of pipe, D is the diameter of pipe, V is the average fluid velocity, and g is the gravitation constant.

The friction factor f depends on the Reynolds number for the flow, and the roughness of the pipe walls.

Example 9.5

What is the head loss in a 5-cm diameter pipe that is 93m long? The friction factor is 0.03, and the average velocity in the pipe is 1.03 m/s.

$$h_L = \frac{fLV^2}{2Dg} = \frac{0.03 \times 93m \times (1.03m/s)^2\ 100}{5cm \times 2 \times 9.8m/s} = 3.02m$$

This would be equivalent to 3.02m × 9.8 kN/m^3 = 29.6 kPa.

Fitting losses are those losses due to couplings and fittings. Fitting losses are normally less than friction losses, and are given by:

$$h_L = \frac{KV^2}{2g} \tag{9.12}$$

where h_L is the head loss due to fittings, K is the head loss coefficient for various fittings, V is the average fluid velocity, and g is the gravitation constant.

Values for K can be found in flow handbooks. Table 9.3 gives some typical values for the head loss coefficient factor in some common fittings.

Example 9.6

Fluid is flowing at 3.7 ft/s through one inch fittings as follows: 7 × 90° ells, 5 tees, 2 gate valves, and 19 couplings. What is the head loss?

$$h_L = \frac{(7 \times 1.5 + 5 \times .08 + 2 \times 0.22 + 19 \times 0.085)3.7 \times 3.7}{2 \times 32.2}$$

$$h_L = (10.5 + 4.0 + 0.44 + 1.615)\ 0.2 = 3.3 \text{ ft}$$

To take into account losses due to friction and fittings, the Bernouilli Equation is modified as follows:

$$\frac{P_A}{\gamma_A} + \frac{V_A^2}{2g} + Z_A = \frac{P_B}{\gamma_B} + \frac{V_B^2}{2g} + Z_B + h_{Lfriction} + h_{Lfittings} \tag{9.13}$$

Table 9.3 Typical Head Loss Coefficient Factors for Fittings

Threaded ell—1 in	1.5	Flanged ell—1 in	0.43
Threaded tee—1 in inline	0.9	Branch	1.8
Globe valve (threaded)	8.5	Gauge valve (threaded)	0.22
Coupling or union—1 in	0.085	Bell mouth reducer	0.05

Form drag is the impact force exerted on devices protruding into a pipe due to fluid flow. The force depends on the shape of the insert, and can be calculated from:

$$F = C_D \gamma \frac{AV^2}{2g} \tag{9.14}$$

where F is the force on the object, C_D is the drag coefficient, γ is the specific weight, g is the acceleration due to gravity, A is the cross-sectional area of obstruction, and V is the average fluid velocity.

Flow handbooks contain drag coefficients for various objects. Table 9.4 gives some typical drag coefficients.

Example 9.7

A 7.3-in diameter ball is traveling through the air with a velocity of 91 ft/s. If the density of the air is 0.0765 lb/ft^3 and C_D = 0.35, what is the force acting on the ball?

$$F = C_D \gamma \frac{AV^2}{2g} = \frac{0.35 \times 0.0765 lb/ft^3 \times \pi \times 7.3^2\ ft^2 \times (91 ft/s)^2}{2 \times 32.2 ft/s^2 \times 4 \times 144} = 1.0 lb$$

9.3 Flow Measuring Instruments

Flow measurements can be divided into the following groups: flow rate, total flow, and mass flow. The choice of measuring device will depend on the required accuracy, flow rate, range, and fluid characteristics (i.e., gas, liquid, suspended particulates, temperature, viscosity, and so forth).

9.3.1 Flow Rate

Many flow measurement instruments use indirect measurements, such as differential pressures, to measure the flow rate. These instruments measure the differential pressures produced when a fluid flows through a restriction. Differential pressure measuring sensors were discussed in Chapter 7. The differential pressure produced is directly proportional to flow rate. Such commonly used restrictions are the (a) orifice plate, (b) Venturi tube, (c) flow nozzle, and (d) Dall tube.

The *orifice plate* is normally a simple metal diaphragm with a constricting hole. The diaphragm is normally clamped between pipe flanges to give easy access. The differential pressure ports can be located in the flange on either side of the orifice plate, or alternatively, at specific locations in the pipe on either side of the flange, as

Table 9.4 Typical Drag Coefficient Values for Objects Immersed in Flowing Fluid

Circular cylinder with axis perpendicular to flow	0.33 to 1.2
Circular cylinder with axis parallel to flow	0.85 to 1.12
Circular disk facing flow	1.12
Flat plate facing flow	1.9
Sphere	0.1+

determined by the flow patterns (named vena contracta), as shown in Figure 9.5. Shown also is the pressure profile. A differential pressure gauge is used to measure the difference in pressure between the two ports. The differential pressure gauge can be calibrated in flow rates. The lagging edge of the hole in the diaphragm is beveled to minimize turbulence. In fluids, the hole is normally centered in the diaphragm, as shown in Figure 9.6(a). However, if the fluid contains particulates, the hole could be placed at the bottom of the pipe, as shown in Figure 9.6(b), to prevent a buildup of particulates. The hole also can be in the form of a semicircle having the same diameter as the pipe, and located at the bottom of the pipe, as shown in Figure 9.6(c).

The flow rate Q in a differential flow rate meter is given by:

$$Q = K\left(\frac{\pi}{4}\right)\left(\frac{d_S}{d_P}\right)^2 \sqrt{2gh} \tag{9.15}$$

where K is the flow coefficient constant, d_S is the diameter of the orifice, d_P is the pipe diameter, and h is the difference in height between P_H and P_L.

Example 9.8

In a 30-in diameter pipe, a circular orifice has a diameter of 20 in, and the difference in height of the manometer levels is 2.3 ft. What is the flow rate in cubic feet per second, if K is 0.97?

$$Q = 0.97\left(\frac{3.14}{4}\right)\left(\frac{20}{30}\right)^2 \sqrt{2 \times 32.2 \times 2.3}$$

$$Q = 4.12 \text{ ft}^3/\text{s}$$

The *Venturi tube*, shown in Figure 9.7(a), uses the same differential pressure principal as the orifice plate. The Venturi tube normally uses a specific reduction in tube size, and is normally well suited for use in larger diameter pipes, but it becomes

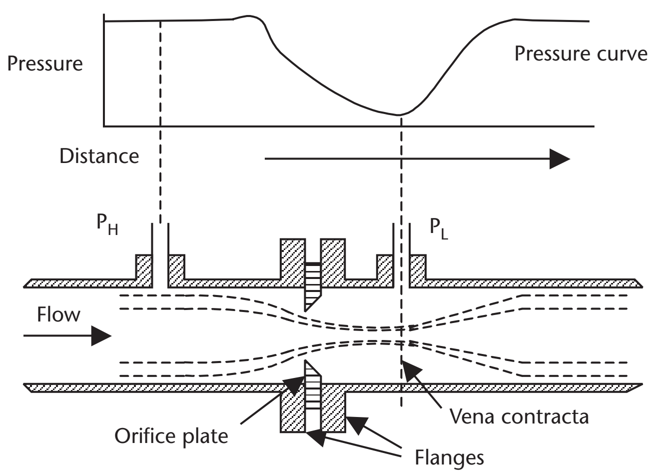

Figure 9.5 Orifice constriction plate with pressure profile.

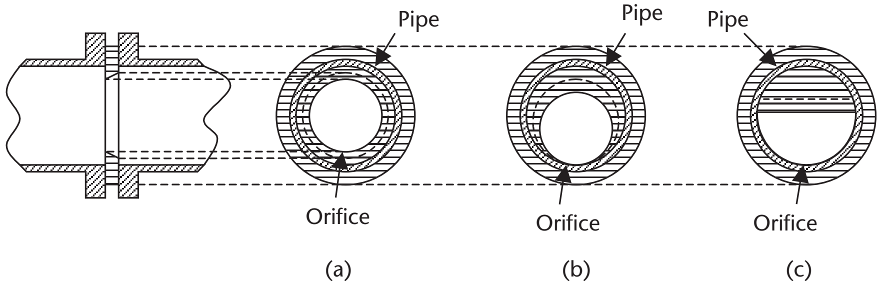

Figure 9.6 Orifice shapes and locations used (a) with fluids, and (b, c) with suspended solids.

heavy and excessively long. One advantage of the Venturi tube is its ability to handle large amounts of suspended solids. It creates less turbulence and insertion loss than the orifice plate. The differential pressure taps in the Venturi tube are located at the minimum and maximum pipe diameters. The Venturi tube has good accuracy, but is expensive.

The *flow nozzle* is a good compromise on cost and accuracy between the orifice plate and the Venturi tube for clean liquids. It is not normally used with suspended particles. Its main use is the measurement of steam flow. The flow nozzle is shown in Figure 9.7(b).

The *Dall tube*, as shown in Figure 9.7(c), has the lowest insertion loss, but is not suitable for use with slurries.

A typical ratio (i.e., a beta ratio, which is the diameter of the orifice opening (d) divided by the diameter of the pipe (D)) for the size of the constriction of pipe size in flow measurements is normally between 0.2 and 0.6. The ratios are chosen to give sufficiently high pressure drops for accurate flow measurements, but not high enough to give turbulence. A compromise is made between high beta ratios (d/D), which give low differential pressures, and low ratios, which give high differential

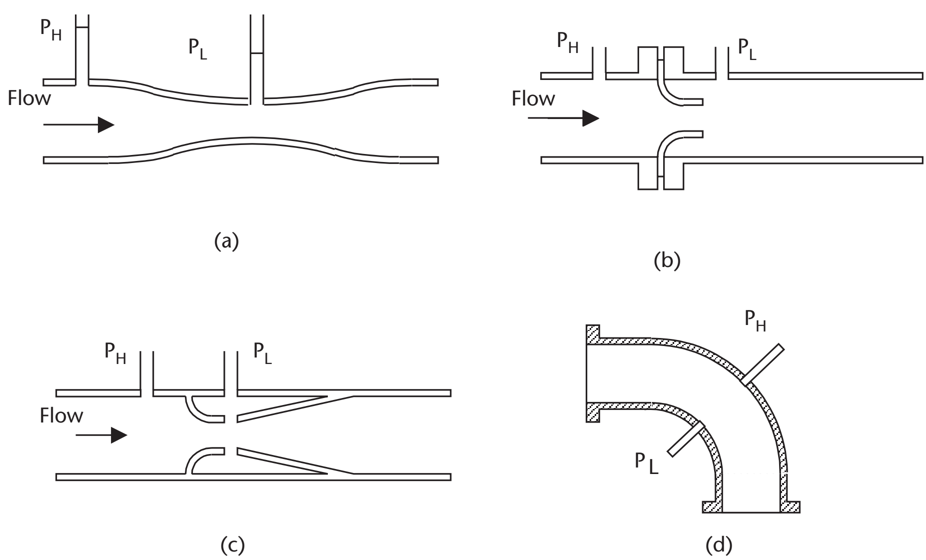

Figure 9.7 Types of constrictions used to measure flow: (a) Venturi tube, (b) flow nozzle, (c) Dall tube, and (d) elbow.

pressures but can create high losses. The Dall tube has the advantage of having the lowest insertion loss, but it cannot be used with slurries.

The *elbow* can be used as a differential flow meter. Figure 9.7(d) shows the cross section of an elbow. When a fluid is flowing, there is a differential pressure between the inside and outside of the elbow, due to the change in direction of the fluid. The pressure difference is proportional to the flow rate of the fluid. The elbow meter is good for handling particulates in solution, and has good wear and erosion resistance characteristics, but has low sensitivity.

In an elbow, the flow is given by;

$$\text{Flow} = C\sqrt{\left(RP_D D^3 \rho\right)} \tag{9.16}$$

where C is a constant, R is the center line radius of the elbow, P_D is the differential pressure, D is the diameter of the elbow, and ρ is the density of the fluid.

The *pilot static tube*, as shown in Figure 9.8, is an alternative method of measuring flow rate, but has a disadvantage, in that it really measures fluid velocity at the nozzle. Because the velocity varies over the cross section of the pipe, the pilot static tube should be moved across the pipe to establish an average velocity, or the tube should be calibrated for one area. Other disadvantages are that the tube can become clogged with particulates, and that the differential pressure between the impact and static pressures for low flow rates may not be enough to give the required accuracy. The differential pressures in any of the above devices can be measured using the pressure measuring sensors discussed in Chapter 7 (Pressure).

In a pilot static tube, the flow Q is given by:

$$Q = K\sqrt{(\rho_s - \rho_I)} \tag{9.17}$$

where K is a constant, p_S is the static pressure, and p_I is the impact pressure.

Variable-area meters, such as the *rotameter* shown in Figure 9.9(a), are often used as a direct visual indicator for flow rate measurements. The rotameter is a vertical tapered tube with a T (or similar) shaped weight, and the tube is graduated in flow rate for the characteristics of the gas or liquid flowing up the tube. The velocity of a fluid or gas flowing decreases as it goes higher up the tube, due to the increase in the bore of the tube. Hence, the buoyancy on the weight reduces as it goes higher up

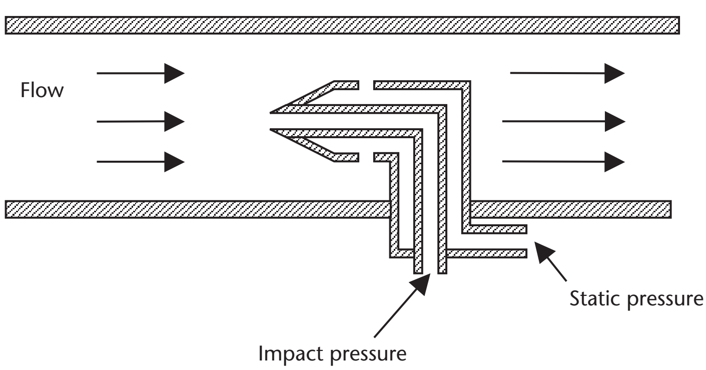

Figure 9.8 Pilot static tube.

the tube. An equilibrium point is eventually reached, where the force on the weight due to the flowing fluid is equal to that of the weight (i.e., the higher the flow rate, the higher the weight goes up the tube). The position of the weight also is dependent on its size and density, the viscosity and density of the fluid, and the bore and taper of the tube. The rotameter has low insertion loss, and has a linear relationship to flow rate. In cases where the weight is not visible, such as an opaque tube used to reduce corrosion, it can be made of a magnetic material, and tracked by a magnetic sensor on the outside of the tube. The rotameter can be used to measure differential pressures across a constriction or flow in both liquids and gases [3].

Vortex flow meters are based on the fact that an obstruction in a fluid or gas flow will cause turbulence or vortices. In the case of the vortex precession meter (for gases), the obstruction is shaped to give a rotating or swirling motion forming vortices, which can be measured ultrasonically. See Figure 9.9(b). The frequency of the vortex formation is proportional to the rate of flow. This method is good for high flow rates. At low flow rates, the vortex frequency tends to be unstable.

Rotating flow rate devices are rotating sensors. One example is the turbine flow meter, which is shown in Figure 9.10(a). The turbine rotor is mounted in the center of the pipe and rotates at a speed proportional to the rate of flow of the fluid or gas passing over the blades. The turbine blades are normally made of a magnetic material or ferrite particles in plastic, so that they are unaffected by corrosive liquids. A Hall device or an MRE sensor attached to the pipe can sense the rotating blades. The turbine should be only used with clean fluids, such as gasoline. The rotating flow devices are accurate, with good flow operating and temperature ranges, but are more expensive than most of the other devices.

Pressure flow meters use a strain gauge to measure the force on an object placed in a fluid or gas flow. The meter is shown in Figure 9.10(b). The force on the object is proportional to the rate of flow. The meter is low-cost, with medium accuracy.

A *moving vane* type of device can be used in a pipe configuration or an open channel flow. The vane can be spring loaded and have the ability to pivot. By measuring the angle of tilt, the flow rate can be determined.

Electromagnetic flow meters only can be used in conductive liquids. The device consists of two electrodes mounted in the liquid on opposite sides of the pipe. A

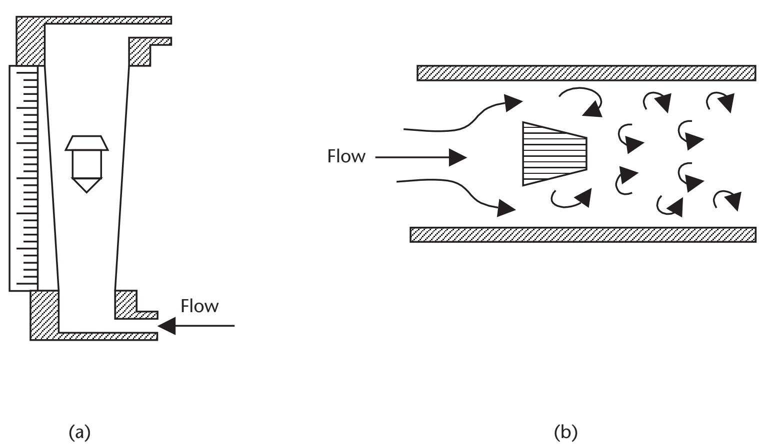

Figure 9.9 Other flow measuring devices: (a) rotameter, and (b) vortex flow meter.

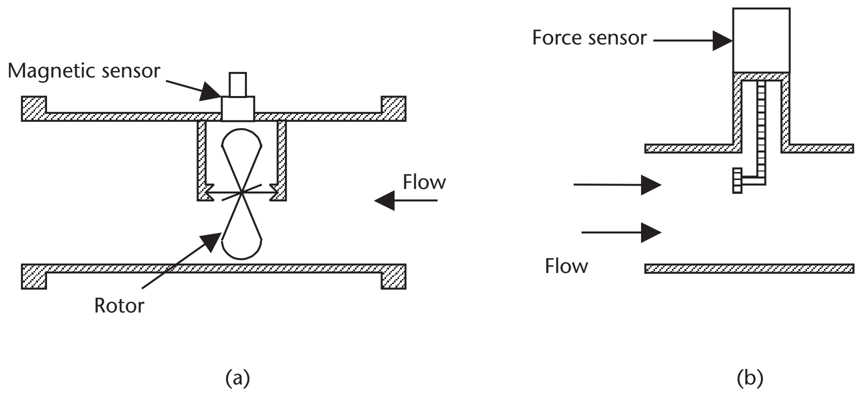

Figure 9.10 Flow rate measuring devices: (a) turbine, and (b) pressure flow meter.

magnetic field is generated across the pipe perpendicular to the electrodes, as shown in Figure 9.11. The conducting fluid flowing through the magnetic field generates a voltage between the electrodes, which can be measured to give the rate of flow. The meter gives an accurate linear output voltage with flow rate. There is no insertion loss, and the readings are independent of the fluid characteristics, but it is a relatively expensive instrument [4].

Ultrasonic flow meters can be transit-time flow meters, or can use the Doppler effect. In the transit-time flow meter, two transducers with receivers are mounted diametrically opposite to each other, but inclined at 45° to the axis of the pipe, as shown in Figure 9.12. Each transducer transmits an ultrasonic beam at a frequency of approximately 1 MHz, which is produced by a piezoelectric crystal. The transit time of each beam is different due to the liquid flow. The difference in transit time of the two beams is used to calculate the average liquid velocity. The advantage of this type of sensor is that the effects of temperature density changes cancel in the two beams. There is no obstruction to fluid flow, and corrosive or varying flow rates are not a problem, but the measurements can be affected by the Reynolds number or velocity profile. The transmitters can be in contact with the liquid, or can be clamped externally on to the pipe.

The Doppler flow meter measures the velocity of entrapped gas ($>30\ \mu$) or small particles in the liquid, as shown in Figure 9.13. A single transducer and receiver are mounted at 45° to the axis of the pipe. The receiver measures the

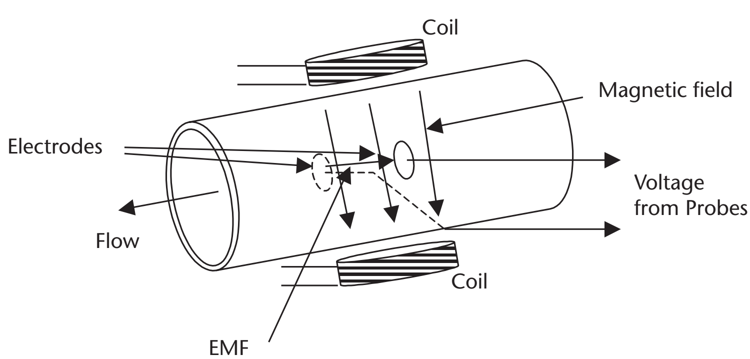

Figure 9.11 Magnetic flow meter.

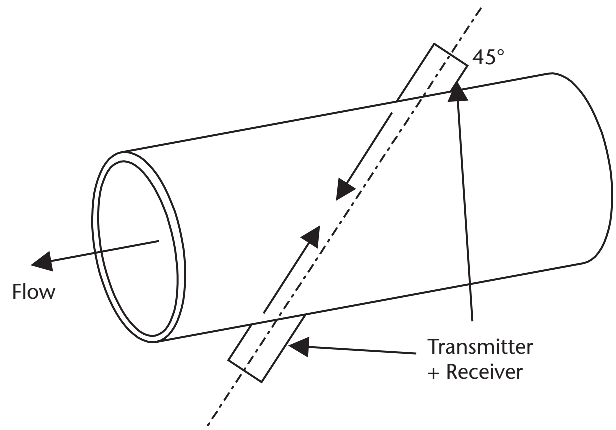

Figure 9.12 Ultrasonic transit-time flow meter.

difference in frequency of the transmitted and received signals, from which the flow velocity can be calculated. The meter can be mounted externally, and is not affected by changes in liquid viscosity.

Ultrasonic flow meters are normally used to measure flow rates in large diameter, nonporous pipes (e.g., cast iron, cement, or fiberglass), and they require periodic recalibration. Meters must not be closer than 10m to each other to prevent interference. This type of meter has a temperature operating range of −20° to +250°C and an accuracy of ±5% FSD.

9.3.2 Total Flow

Positive displacement meters are used to measure the total quantity of fluid flowing, or the volume of liquid in a flow. The meters use containers of known size, which are filled and emptied a known number of times in a given time period, to give the total flow volume. The common types of instruments for measuring total flow are:

- The Piston flow meter;
- Rotary piston;
- Rotary vane;

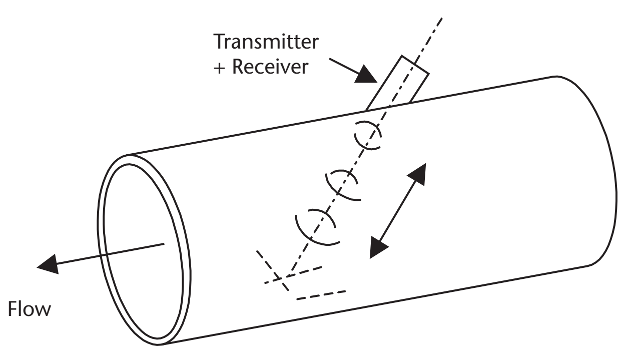

Figure 9.13 Ultrasonic Doppler flow meter.

- Nutating disk;
- Oval gear.

Piston meters consist of a piston in a cylinder. Initially, the fluid enters on one side of the piston and fills the cylinder, at which point the fluid is diverted to the other side of the piston via valves, and the outlet port of the full cylinder is opened. The redirection of fluid reverses the direction of the piston and fills the cylinder on the other side of the piston. The number of times the piston traverses the cylinder in a given time frame determines the total flow. The piston meter is shown in Figure 9.14. The meter has high accuracy, but is expensive.

Nutating disk meters are in the form of a disk that oscillates, allowing a known volume of fluid to pass with each oscillation. The meter is illustrated in Figure 9.15. Liquid enters and fills the left chamber. Because the disk is off center, the liquid pressure causes the disk to wobble. This action empties the volume of liquid from the left chamber to the right chamber, the left chamber is then refilled, and the liquid in the right chamber exits. The oscillations of the disk are counted and the total volume measured. This meter is not suitable for measuring slurries. The meter is accurate and expensive, but a low-cost version is available, which is used in domestic water metering and industrial liquid metering [5].

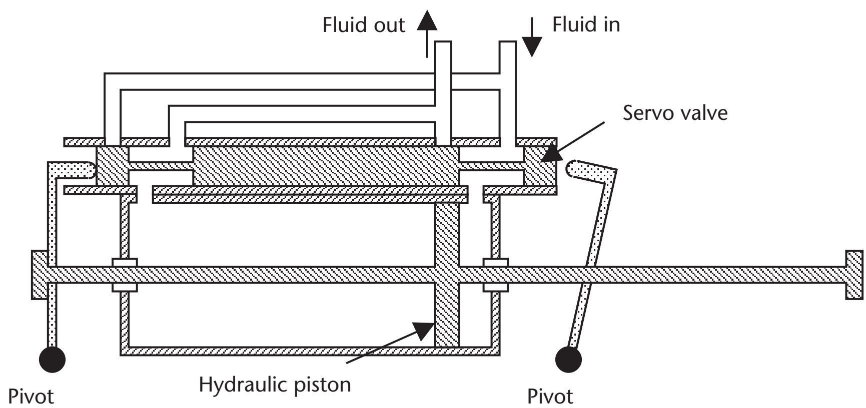

Figure 9.14 Piston meter.

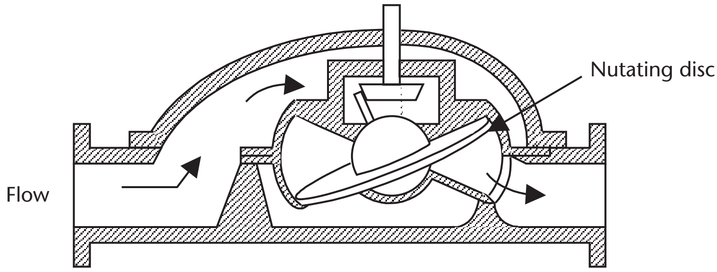

Figure 9.15 Nutating disk flow meter.

Velocity meters, normally used to measure flow rate, also can be set up to measure total flow. Multiplying the velocity by the cross-sectional area of the meter can measure total flow.

9.3.3 Mass Flow

By measuring the flow rate and knowing the density of a fluid, the mass of the flow can be measured. Mass flow instruments include constant speed impeller turbine wheel-spring combinations, which relate the spring force to mass flow, and devices that relate heat transfer to mass flow [6].

Coriolis flow meters, which can be used to measure mass flow, can be either in the form of a straight tube or a loop. In either case, the device is forced into resonance perpendicular to the flow direction. The resulting coriolis force produces a twist movement in the pipe or loop that can be measured and related to the mass flow. See Figure 9.16. The loop has a wider operating range than the straight tube, is more accurate at low flow rates, and can be used to measure both mass flow and density.

The *anemometer* is a method that can be used to measure gas flow rates. One method is to keep the temperature of a heating element in a gas flow constant and measure the power required. The higher the flow rates, the higher the amount of heat required. The alternative method (hot-wire anemometer) is to measure the incident gas temperature, and the temperature of the gas downstream from a heating element. The difference in the two temperatures can be related to the flow rate [7]. Micromachined anemometers are now widely used in automobiles for the measurement of air intake mass, as described in Chapter 6, Figure 6.13. The advantages of this type of sensor are that they are very small, have no moving parts, have minimal obstruction to flow, have a low thermal time constant, and are very cost effective with good longevity.

9.3.4 Dry Particulate Flow Rate

Dry particulate flow rate on a conveyer belt can be measured with the use of a load cell. This method is illustrated in Figure 9.17. To measure flow rate, it is only necessary to measure the weight of material on a fixed length of the conveyer belt [8].

The flow rate Q is given by:

$$Q = WR/L \tag{9.18}$$

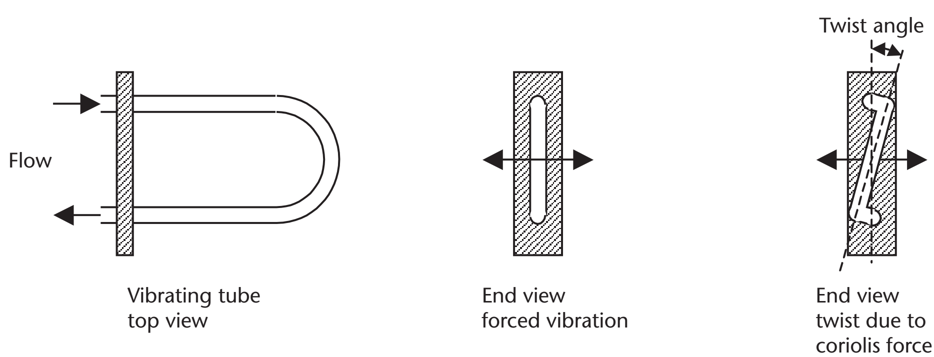

Figure 9.16 Mass flow meter using coriolis force.

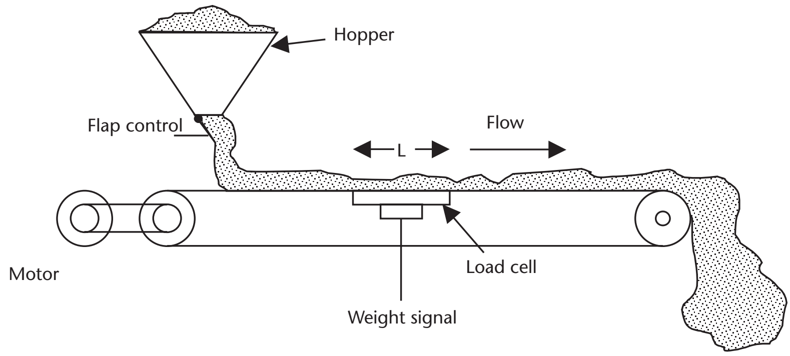

Figure 9.17 Conveyer belt system for the measurement of dry particulate flow rate.

where W is the weight of material on length L of the weighing platform, and R is the speed of the conveyer belt.

Example 9.9

A conveyer belt is traveling at 27 cm/s, and a load cell with a length of 0.72m is reading 5.4 kg. What is the flow rate of the material on the belt?

$$Q = \frac{5.4 \times 27}{100 \times 0.72} \, kg/s = 2.025 \, kg/s$$

9.3.5 Open Channel Flow

Open channel flow occurs when the fluid flowing is not contained as in a pipe, but is in an open channel. Flow rates can be measured using constrictions, as in contained flows. A Weir sensor used for open channel flow is shown in Figure 9.18(a). This device is similar in operation to an orifice plate. The flow rate is determined by measuring the differential pressures or liquid levels on either side of the constriction. A Parshall flume, which is similar in shape to a Venturi tube, is shown in Figure 9.18(b). A paddle wheel and an open flow nozzle are alternative methods of measuring open channel flow rates.

9.4 Application Considerations

Many different types of sensors can be used for flow measurements. The choice of any particular device for a specific application depends on a number of factors, such as: reliability, cost, accuracy, pressure range, size of pipe, temperature, wear and erosion, energy loss, ease of replacement, particulates, viscosity, and so forth [9].

9.4.1 Selection

The selection of a flow meter for a specific application to a large extent will depend upon the required accuracy and the presence of particulates, although the required accuracy is sometimes downgraded because of cost. One of the most accurate meters is the magnetic flow meter, which can be accurate to 1% of FSD. This meter

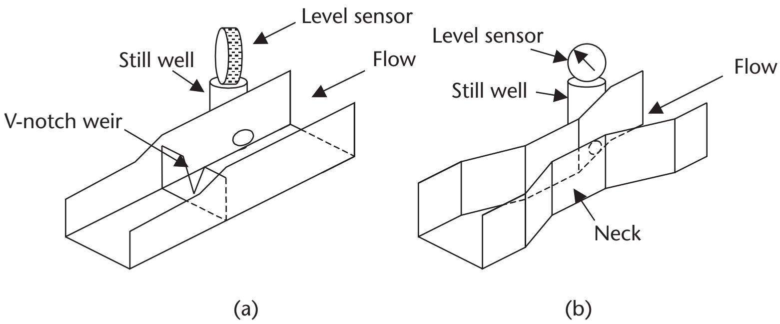

Figure 9.18 Open channel flow sensors: (a) Weir, and (b) Parshall flume.

is good for low flow rates with high viscosities, and has low energy loss, but is expensive and requires a conductive fluid.

The turbine gives high accuracies, and can be used when there is vapor present, but the turbine is better with clean, low viscosity fluids. Table 9.5 gives a comparison of flow meter characteristics [10].

The most commonly used general-purpose devices are the pressure differential sensors used with pipe constrictions. These devices will give an accuracy in the 3% range when used with solid state pressure sensors, which convert the readings directly into electrical units, or the rotameter for direct visual reading. The Venturi tube has the highest accuracy and least energy loss, followed by the flow nozzle, then the orifice plate. For cost effectiveness, the devices are in the reverse order. If large amounts of particulates are present, the Venture tube is preferred. The differential pressure devices operate best between 30% and 100% of the flow range. The elbow also should be considered in these applications.

Gas flow can be best measured with an anemometer. Solid state anemometers are now available with good accuracy and very small size, and are cost effective.

For open channel applications, the flume is the most accurate, and is preferred if particulates are present, but is the most expensive.

Table 9.5 Summary of Flow Meter Characteristics

Meter Type	*Range*	*Accuracy*	*Comments*
Orifice plate	3 to 1	±3% FSD	Low cost and accuracy
Venturi tube	3 to 1	±1% FSD	High cost, good accuracy, low losses
Flow nozzle	3 to 1	±2% FSD	Medium cost and accuracy
Dall tube	3 to 1	±2% FSD	Medium cost and accuracy, low losses
Elbow	3 to 1	±6%–10% FSD	Low cost, losses, and sensitivity
Pilot static tube	3 to 1	±4% FSD	Low sensitivity
Rotameter	10 to 1	±2% of rate	Low losses, line of sight
Turbine meter	10 to 1	±2% FSD	High accuracy, low losses
Moving vane	5 to 1	±10% FSD	Low cost, low accuracy
Electromagnetic	30 to 1	±0.5% of rate	Conductive fluid, low losses, high cost
Vortex meter	20 to 1	±0.5% of rate	Poor at low flow rates
Strain gauge	3 to 1	±2% FSD	Low cost, and accuracy
Ultrasonic meter	30 to1	±5% FSD	Doppler 15 to 1 range, large diameter pipe
Nutating disk	5 to 1	±3% FSD	High accuracy and cost
Anemometer	100 to 1	±2% of rate	Low losses, fast response

Particular attention also should be given to manufacturers' specifications and application notes.

9.4.2 Installation

Because of the turbulence generated by any type of obstruction in an otherwise smooth pipe, attention must be given to the placement of flow sensors. The position of the pressure taps can be critical for accurate measurements. The manufacturers' recommendations should be followed during installation. In differential pressure sensing devices, the upstream tap should be at a distance from 1 to 3 pipe diameters from the plate or constriction, and the downstream tap up to 8 pipe diameters from the constriction.

To minimize pressure fluctuations at the sensor, it is desirable to have a straight run of 10 to 15 pipe diameters on either side of the sensing device. It also may be necessary to incorporate laminar flow planes into the pipe to minimize flow disturbances, and dampening devices to reduce flow fluctuations to an absolute minimum.

Flow nozzles may require vertical installation if gases or particulates are present. To allow gases to pass through the nozzle, it should be facing upward; and for particulates, facing downward.

9.4.3 Calibration

Flow meters need periodic calibration. This can be done by using another calibrated meter as a reference, or by using a known flow rate. Accuracy can vary over the range of the instrument, and with temperature and specific weight changes in the fluid. Thus, the meter should be calibrated over temperature as well as range, so that the appropriate corrections can be made to the readings. A spot check of the readings should be made periodically to check for instrument drift, which may be caused by the instrument going out of calibration, or particulate buildup and erosion.

9.5 Summary

This chapter discussed the flow of fluids in closed and open channels, and gases in closed channels. Liquid flow can be laminar or turbulent, depending upon the flow rate and its Reynolds number. The Reynolds number is related to the viscosity, pipe diameter, and liquid density. The various continuity and flow equations are used in the development of the Bernoulli equation, which uses the concept of the conservation of energy to relate pressures to flow rates. The Bernoulli equation can be modified to allow for losses in liquids due to viscosity, friction with the constraining tube walls, and drag.

Many types of sensors are available for measuring the flow rates in gases, liquids, slurries, and free-flowing solids. The sensors vary, from tube constrictions where the differential pressure across the constriction is used to obtain the flow rate, to electromagnetic flow meters, to ultrasonic devices. Flow rates can be measured in volume, total, or mass. The choice of sensor for measuring flow rates will depend on many factors, such as accuracy, particulates, flow velocity, range, pipe size, viscosity, and so forth. Only experienced technicians should perform installation and calibration.

Definitions

Bernoulli equation is an equation for flow based on the conservation of energy.

Flow rate is the volume of fluid or gas passing a given point in a given amount of time.

Laminar flow in a liquid occurs when its average velocity is comparatively low, and $R < 2,000$. The flow is streamlined and laminar without eddies.

Mass flow is the mass of liquid or gas flowing in a given time period.

Reynolds number (R) is a derived relationship, combining the density and viscosity of a liquid, with its velocity of flow and the cross-sectional dimensions of the flow.

Total flow is the volume of liquid or gas flowing in a given period of time.

Turbulent flow in a liquid occurs when the flow velocity is high, and $R >$ 5,000. The flow breaks up into fluctuating velocity patterns and eddies.

Velocity in fluids is the average rate of fluid flow across the diameter of the pipe.

Viscosity is a property of a gas or liquid that measures its resistance to motion or flow.

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