CHAPTER 16

Flow Measurement

Chapter Outline

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16.1 Introduction

We now move on to look at flow measurement in this chapter. Flow measurement is concerned with quantifying the rate of flow of materials. Such a measurement is quite a common requirement in the process industries. The material measured may be in either a solid, liquid, or gaseous state. When the material is in a solid state, the flow can only be quantified as the mass flow rate, this being the mass of material that flows in one unit of time. When the material is in a liquid or gaseous state, the flow can be quantified either as the mass flow rate or the volume flow rate, the latter being the volume of material that flows in one unit of time. Of the two, a flow measurement in terms of the mass flow rate is preferred if very accurate measurement is required. The greater accuracy of mass flow measurement arises from the fact that mass is invariant whereas volume is a variable quantity.

A particular complication in the measurement of flow rate of liquids and gases that are flowing in pipes is the need to consider whether the flow is laminar or turbulent. Laminar flow is characterized by a motion of the fluid being in a direction parallel to the sides of the pipe, and it occurs in straight lengths of pipe when the fluid is flowing at a low velocity. However, it should be noted that even laminar flow is not uniform across the cross section of the pipe, with the velocity being greatest at the center of the pipe and decreasing to zero immediately next to the wall of the pipe. By contrast, turbulent flow involves a complex pattern of flow that is not in a uniform direction. Turbulent flow occurs in nonstraight sections of pipe and also occurs in straight sections when the fluid velocity exceeds a critical value. Because of the difficulty in measuring turbulent flow, the usual practice is to restrict flow measurement to places where the flow is laminar, or at least approximately laminar. This can be achieved by measuring the flow in the center of a long, straight length of pipe if the flow velocity is below the critical velocity for turbulent flow. In the case of high mean fluid velocity, it is often possible to find somewhere within the flow path where a larger diameter pipe exists and therefore the flow velocity is lower.

16.2 Mass Flow Rate

The method used to measure mass flow rate is determined by whether the measured quantity is in a solid, liquid, or gaseous state, since different techniques are appropriate for each. The main techniques available for measuring mass flow rate are summarized below.

16.2.1 Conveyor-Based Methods

Conveyor-based methods are appropriate for measuring the flow of solids that are in the form of powders or small granular particles. Such powders and particles are commonly produced by crushing or grinding procedures in process industries, and a conveyor is a very suitable means of transporting materials in this form. Transporting materials on a conveyor allows the mass flow rate to be calculated in terms of the mass of material on a given length of conveyor multiplied by the speed of the conveyor. Figure 16.1 shows a typical measurement system. A load cell measures the mass M of material distributed over a length L of the conveyor. If the conveyor velocity is v, the mass flow rate Q is given by

$$Q = Mv/L$$

As an alternative to weighing the flowing material, a *nuclear mass-flow sensor* can be used, in which a gamma ray source is directed at the material being transported along the conveyor. The material absorbs some radiation, and the amount of radiation received by a detector on the other side of the material indicates the amount of material on the conveyor. This technique has obvious safety concerns, and is therefore subject to licensing and strict regulation.

16.2.2 Coriolis Flowmeter

As well as sometimes being known by the alternative name of *inertial flowmeter*, the Coriolis flowmeter is often referred to simply as a *mass flowmeter* because of its dominance in the mass flowmeter market. However, this assumption that a mass flowmeter always refers to a Coriolis meter is wrong, since several other types of devices are available to measure mass flow, although it is true to say that they are much less common than Coriolis meters.

Coriolis meters are primarily used to measure the mass flow rate of liquids, although they have also been successfully used in some gas flow measurement applications. The flowmeter consists either of a pair of parallel vibrating tubes or else as a single vibrating

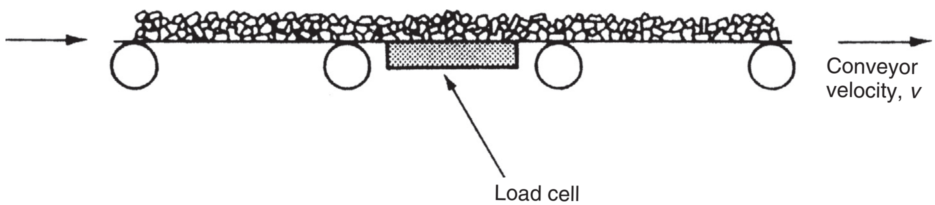

Figure 16.1
Conveyor-based mass flow rate measurement.

tube that is formed into a configuration that has two parallel sections. The two vibrating tubes (or the two parallel sections of a single tube) deflect according to the mass flow rate of the measured fluid that is flowing inside. Tubes are made of various materials, of which stainless steel is the most common. They are also manufactured in different shapes such as B-shaped, D-shaped, U-shaped, triangular-shaped, helix-shaped, and straight. These alternative shapes are sketched in Figure 16.2(a) and a U-shaped tube is shown in more detail in Figure 16.2(b). The tubes are anchored at two points. An electromechanical drive unit, positioned midway between the two anchors, excites vibrations in each tube at the tube resonant frequency. The vibrations in the two tubes, or the two parallel sections of a single tube, are 180° out of phase. The vibratory motion of each tube causes forces on the particles in the flowing fluid. These forces induce motion

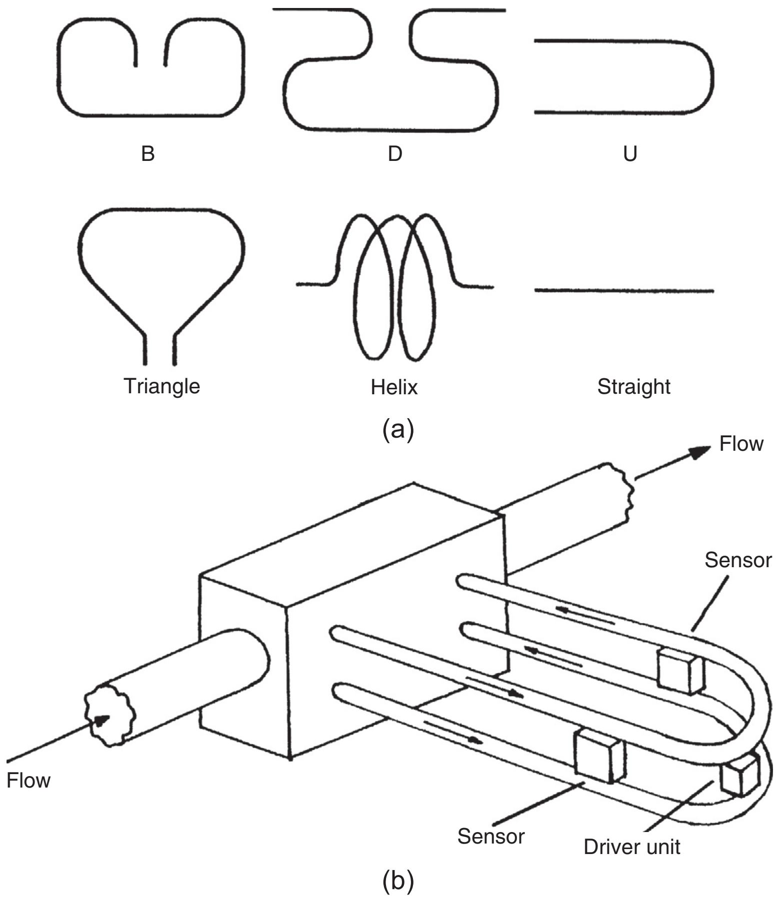

Figure 16.2
(a) Coriolis flowmeter shapes and (b) detail of the U-shaped Coriolis flowmeter.

of the fluid particles in a direction that is orthogonal to the direction of flow, and this produces a Coriolis force. This Coriolis force causes a deflection of the tubes that is superimposed on top of the vibratory motion. The net deflection of one tube relative to the other is given by $d = kfR$, where k is a constant, f is the frequency of the tube vibration, and R is the mass flow rate of the fluid inside the tube. This deflection is measured by a suitable sensor.

Coriolis meters give excellent accuracy, with measurement uncertainties of $\pm 0.2\%$ being typical. They also have low maintenance requirements. However, apart from being expensive (typical cost is $6000), they suffer from a number of operational problems. Failure may occur after a period of use because of mechanical fatigue in the tubes. Tubes are also subject to both corrosion caused by chemical interaction with the measured fluid and abrasion caused by particles within the fluid. Diversion of the flowing fluid around the flowmeter causes it to suffer a significant pressure drop, though this is much less evident in straight tube designs.

16.2.3 Thermal Mass Flow Measurement

Thermal mass flowmeters are primarily used to measure the flow rate of gases. The structure of this device is shown in Figure 16.3. The principle of operation is to direct the flowing material past a heated element and measure the temperature of the flowing material before and after the heater. The temperatures on either side of the heater are commonly measured by a platinum resistance thermometer inside a protective sheath. The mass flow rate is inferred in one of the two ways: (1) by measuring the temperature rise in the flowing material or (2) by measuring the heater power required to achieve a constant set temperature difference in the flowing material. In both cases, the specific heat and density of the flowing fluid must be known. Typical measurement

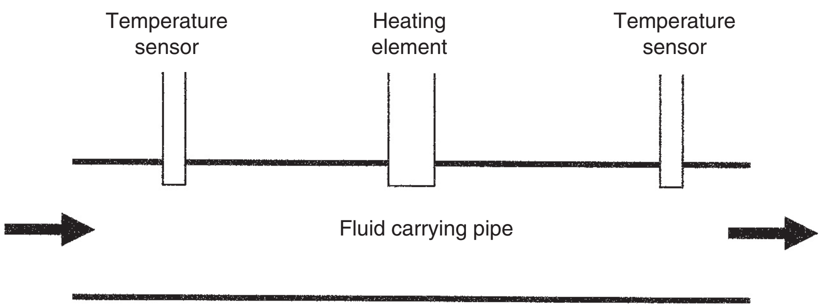

Figure 16.3
Structure of the thermal mass flowmeter.

uncertainty is ±2%. Standard instruments require the measured gas to be clean and noncorrosive. However versions made from special alloys can cope with more aggressive gases.

MEMS thermal mass flowmeters are also now available. These have the same basic structure as shown in Figure 16.3, but of course the heater and temperature sensors are both MEMS scale and contained within a tiny package. The temperature sensors used are thermopile devices of the form shown in Figure 14.16.

MEMS thermal mass flowmeters have a number of advantages over other forms of diaphragm-based flowmeter, including small size, fast response time, high accuracy, low pressure drop across the device, very low power consumption, and high reliability due to the absence of moving parts. Flow rates up to 100 l/min can typically be measured. However, since this form of sensor also has excellent sensitivity to very small flow rates, devices are available that can measure flow rates in the range of microliters (10^{-6} l) per minute or nanoliters (10^{-9} l) per minute.

16.2.4 Joint Measurement of Volume Flow Rate and Fluid Density

Before the advent of the Coriolis meter, the usual way of measuring mass flow rate was to compute this from separate, simultaneous measurements of the volume flow rate and the fluid density. In many circumstances, this is still the cheapest option, although measurement accuracy is substantially inferior to that provided by a Coriolis meter.

16.3 Volume Flow Rate

Volume flow rate is an appropriate way of quantifying the flow of all materials that are in a gaseous, liquid, or semiliquid slurry form (where solid particles are suspended in a liquid host), although measurement accuracy is inferior to mass flow measurement as noted earlier. Materials in these forms are usually carried in pipes, and various instruments can be used to measure the volume flow rate as described below. As noted in the introduction, these all assume laminar flow. In addition, flowing liquids are sometimes carried in an open channel, in which case the volume flow rate can be measured by an open channel flowmeter.

16.3.1 Differential Pressure (Obstruction-Type) Meters

Differential pressure meters involve the insertion of some device into a fluid-carrying pipe that causes an obstruction and creates a pressure difference on either side of the device. Such meters are sometimes known as obstruction-type meters or flow restriction meters. Devices used to obstruct the flow include the *orifice plate*, the *Venturi tube*, the *flow*

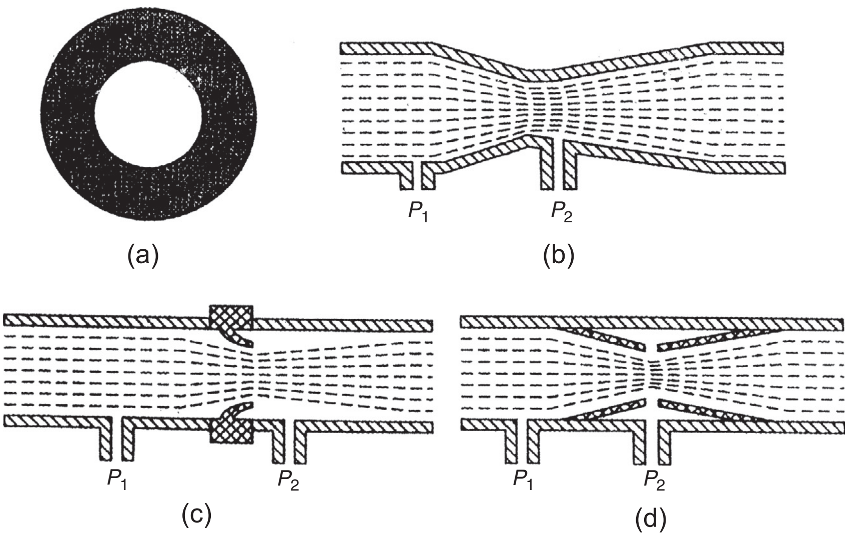

Figure 16.4
Obstruction devices: (a) Orifice plate; (b) venturi; (c) flow nozzle; and (d) Dall flow tube.

nozzle, and the *Dall flow tube*, as illustrated in Figure 16.4. When such a restriction is placed in a pipe, the velocity of the fluid through the restriction increases and the pressure decreases. The volume flow rate is then proportional to the square root of the pressure difference across the obstruction. The manner in which this pressure difference is measured is important. Measuring the two pressures with different instruments and calculating the difference between the two measurements is not satisfactory because of the large measurement error which can arise when the pressure difference is small, as explained in Chapter 3. Therefore, the normal procedure is to use a differential pressure transducer, which is commonly a diaphragm-type device.

The *Pitot static tube* is a further device that measures flow by creating a pressure difference within a fluid-carrying pipe. However, in this case, there is negligible obstruction of flow in the pipe. The Pitot tube is a very thin tube that obstructs only a small part of the flowing fluid and thus measures flow at a single point across the cross section of the pipe. This measurement only equates to average flow velocity in the pipe for the case of uniform flow. The *Annubar* is a type of multiport Pitot tube that does measure the average flow across the cross section of the pipe by forming the mean value of several local flow measurements across the cross section of the pipe.

All applications of this method of flow measurement assume laminar flow by ensuring that the flow conditions upstream of the obstruction device are in steady state, and a certain minimum length of straight run of pipe ahead of the flow measurement point is specified to achieve this. The minimum lengths required for various pipe diameters are specified in standards tables. However, a useful rule of thumb widely used in the process industries is to specify a length of 10 times that of the pipe diameter. If physical restrictions make this impossible to achieve, special flow smoothing vanes can be inserted immediately ahead of the measurement point.

Flow restriction-type instruments are popular because they have no moving parts and are therefore robust, reliable, and easy to maintain. However, one significant disadvantage of this method is that the obstruction causes a permanent loss of pressure in the flowing fluid. The magnitude and hence importance of this loss depends on the type of obstruction element used, but where the pressure loss is large, it is sometimes necessary to recover the lost pressure by an auxiliary pump further down the flow line. This class of device is not normally suitable for measuring the flow of slurries, as the tappings into the pipe to measure the differential pressure are prone to blockage, although the Venturi tube can be used to measure the flow of dilute slurries.

Figure 16.5 illustrates approximately the way in which the flow pattern is interrupted when an orifice plate is inserted into a pipe. The other obstruction devices also have a similar effect to this, although the magnitude of pressure loss is smaller. Of particular interest is the fact that the minimum cross-sectional area of flow occurs not within the obstruction but at a point downstream of there. Knowledge of the pattern of pressure variation along the pipe, as shown in Figure 16.6, is also of importance in using this technique of volume flow rate measurement. This shows that the point of minimum pressure coincides with the point of minimum cross-section flow, a little way downstream of the obstruction. Figure 16.6 also shows that there is a small rise in pressure immediately before the obstruction. It is therefore important not only to position the instrument measuring P_2 exactly at the point of minimum pressure, but also to measure

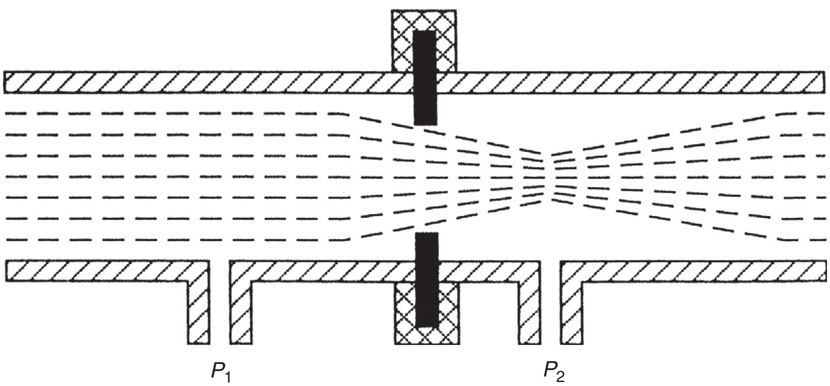

Figure 16.5
Profile of flow across the orifice plate.

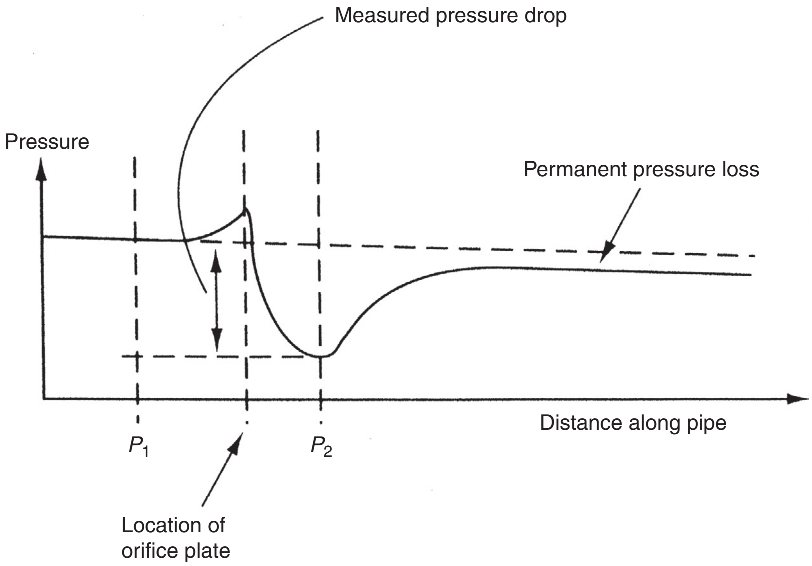

Figure 16.6
Pattern of pressure variation on either side of the orifice plate.

the pressure P_1 at a point upstream of the point where the pressure starts to rise before the obstruction.

In the absence of any heat transfer mechanisms, and assuming frictionless flow of an incompressible fluid through the pipe, the theoretical volume flow rate of the fluid Q is given by

$$Q = \left[\frac{A_2}{\sqrt{1-(A_2/A_1)^2}}\right]\left[\sqrt{\frac{2(P_1-P_2)}{\rho}}\right] \tag{16.1}$$

where A_1 and P_1 are the cross-sectional area and pressure of the fluid flow before the obstruction, A_2 and P_2 are the cross-sectional area and pressure of the fluid flow at the narrowest point of the flow beyond the obstruction, and ρ is the fluid density.

Equation (16.1) is never entirely applicable in practice for two main reasons. First, the flow is always impeded by a friction force, which varies according to the type of fluid and its velocity and is quantified by a constant known as the Reynolds number. Second, the cross-sectional area of the fluid flow ahead of the obstruction device is less than the diameter of the pipe carrying it, and the minimum cross-sectional area of the fluid after the obstruction is less than the diameter of the obstruction. This latter problem means that neither A_1 nor A_2 can be measured accurately. Fortunately, provided the pipe is smooth and therefore the friction force is small, these two problems can be adequately accounted for by applying a constant called the discharge coefficient. This modifies Eqn (16.1) to the following:

$$Q = \left[\frac{C_D A_2'}{\sqrt{1 - \left(A_2'/A_1'\right)^2}}\right]\left[\sqrt{\frac{2(P_1 - P_2)}{\rho}}\right] \tag{16.2}$$

where A_1' and A_2' are the actual pipe diameters before and at the obstruction and C_D is the discharge coefficient that corrects for the friction force and the difference between the pipe and flow cross section diameters.

Before Eqn (16.2) can be evaluated, the discharge coefficient must be calculated. As this varies between each measurement situation, it would appear at first sight that the discharge coefficient must be determined by practical experimentation in every case. However, provided that certain conditions are met, standard tables can be used to obtain the value of the discharge coefficient appropriate to the pipe diameter and fluid involved.

One particular problem with all flow restriction devices is that the pressure drop ($P_1 - P_2$) varies as the square of the flow rate Q according to Eqn (16.2). The difficulty of measuring small pressure differences accurately has already been noted earlier. In consequence, the technique is only suitable for measuring flow rates that are between 30% and 100% of the maximum flow rate that a given device can handle. This means that alternative flow measurement techniques have to be used in applications where the flow rate can vary over a large range that can drop to below 30% of the maximum rate.

Orifice plate

The orifice plate is a metal disc with a concentric hole in it, which is inserted into the pipe carrying the flowing fluid. Orifice plates are simple, cheap, and available in a wide range of sizes. In consequence, they account for almost 50% of the instruments used in industry for measuring volume flow rate. One limitation of the orifice plate is that its inaccuracy is typically at least ±2% and may approach ±5%. Also, the permanent pressure loss caused in the measured fluid flow is between 50% and 90% of the magnitude of the pressure difference ($P_1 - P_2$). Other problems with the orifice plate are a gradual change in the discharge coefficient over a period of time as the sharp edges of the hole wear away, and a tendency for any particles in the flowing fluid to stick behind the hole and thereby gradually reduce its diameter as the particles build up. The latter problem can be minimized by using an orifice plate with an eccentric hole. If this hole is close to the bottom of the pipe, solids in the flowing fluid tend to be swept through, and build up of particles behind the plate is minimized. A very similar problem arises if there are any bubbles of vapor or gas in the flowing fluid when liquid flow is involved. These also tend to build up behind an orifice plate and distort the pattern of flow. This difficulty can be avoided by mounting the orifice plate in a vertical run of pipe.

Venturis and similar devices

A number of obstruction devices are available that are specially designed to minimize the pressure loss in the measured fluid. These have various names such as Venturi, flow nozzle, and Dall flow tube. They are all much more expensive than an orifice plate but have better performance. The smooth internal shape means that they are not prone to solid particles or bubbles of gas sticking in the obstruction, as is likely to happen in an orifice plate. The smooth shape also means that they suffer much less wear, and consequently have a longer life than orifice plates. They also require less maintenance and give greater measurement accuracy.

Venturi: The Venturi has a precision-engineered tube of a special shape. This offers measurement uncertainty of only ±1%. However, the complex machining required to manufacture it means that it is the most expensive of all the obstruction devices discussed. Permanent pressure loss in the measured system is 10−15% of the pressure difference ($P_1 - P_2$) across it.

Dall flow tube: The Dall flow tube consists of two conical reducers inserted into the fluid-carrying pipe. It has a very similar internal shape to the Venturi, except that it lacks a throat. This construction is much easier to manufacture and this gives the Dall flow tube an advantage in cost over the Venturi, although the typical measurement inaccuracy is a little higher (±1.5%). Another advantage of the Dall flow tube is its shorter length, which makes the engineering task of inserting it into the flow line easier. The Dall tube has one further operational advantage, in that the permanent pressure loss imposed on the measured system is only about 5% of the measured pressure difference ($P_1 - P_2$).

Flow nozzle: The flow nozzle is of simpler construction still, and is therefore cheaper than either a Venturi or a Dall flow tube, but the pressure loss imposed on the flowing fluid is 30−50% of the measured pressure difference ($P_1 - P_2$) across the nozzle.

Pitot static tube

The Pitot static tube is mainly used for making temporary measurements of flow, although it is also used in some instances for permanent flow monitoring. It measures the local velocity of flow at a particular point within a pipe rather than the average flow velocity as measured by other types of flowmeter. This may be very useful where there is a requirement to measure local flow rates across the cross section of a pipe in the case of nonuniform flow. Multiple Pitot tubes are normally used to do this.

The instrument depends on the principle that a tube placed with its open end in a stream of fluid, as shown in Figure 16.7, will bring to rest that part of the fluid which impinges on it, and the loss of kinetic energy will be converted to a measurable increase in pressure inside the tube. This pressure (P_1), as well as the static pressure of the undisturbed free

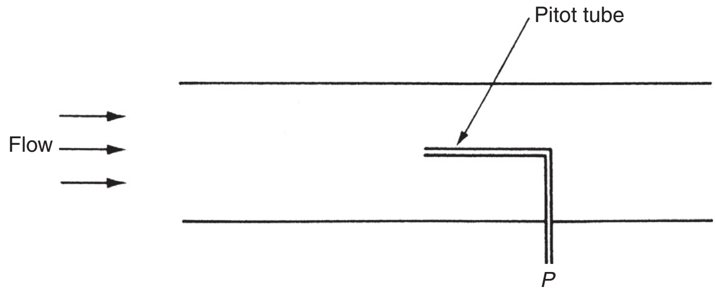

Figure 16.7
Pitot tube.

stream of flow (P_2), is measured. The flow velocity can then be calculated from the formula:

$$v = C\sqrt{2g(P_1 - P_2)}$$

The constant C, known as the Pitot tube coefficient, is a factor which corrects for the fact that not all fluid incident on the end of the tube will be brought to rest: a proportion will slip around it according to the design of the tube. Having calculated v, the volume flow rate can then be calculated by multiplying v by the cross-sectional area of the flow pipe, A.

Pitot tubes have the advantage that they cause negligible pressure loss in the flow. They are also cheap, and the installation procedure consists of the very simple process of pushing them down a small hole drilled in the flow-carrying pipe. Their main failing is that the measurement inaccuracy is typically about ±5%, although more expensive versions can reduce inaccuracy down to ±1%. The *annubar* is a development of the Pitot tube that has multiple sensing ports distributed across the cross section of the pipe and thus provides an approximate measurement of the mean flow rate across the pipe.

16.3.2 Variable Area Flowmeters (Rotameters)

In the variable area flowmeter (which is also sometimes known as a rotameter), the differential pressure caused by fluid flow across a variable aperture is used to adjust the area of the aperture. The aperture area is then a measure of the flow rate. The instrument is reliable and cheap and is used extensively throughout industry, accounting for about 20% of all flowmeters sold. Normally, this type of instrument only gives a visual indication of flow rate, and so it is of no use in automatic control schemes. However, special versions of variable area flowmeters are now available that incorporate fiber optics. In these, a row of fibers detects the position of the float by sensing the reflection of light from it, and an electrical signal output can be derived from this.

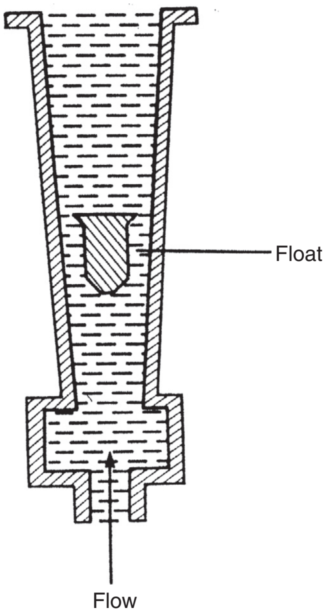

Figure 16.8
Variable area flowmeter.

In its simplest form, shown in Figure 16.8, the instrument consists of a tapered glass tube containing a float which takes up a stable position where its submerged weight is balanced by the upthrust due to the differential pressure across it. The position of the float is a measure of the effective annular area of the flow passage and hence of the flow rate. The inaccuracy of the cheapest instruments is typically ±5%, but more expensive versions offer measurement inaccuracies as low as ±0.5%.

16.3.3 Positive Displacement Flowmeters

Positive displacement flowmeters account for nearly 10% of the total number of flowmeters used in industry and are used in large numbers for metering domestic gas and water consumption. The cheapest instruments have a typical inaccuracy of about ±2%, but the inaccuracy in more expensive ones can be as low as ±0.5%. These higher quality instruments are used extensively within the oil industry, as such applications can justify the high cost of such instruments.

All positive displacement meters operate by using mechanical divisions to displace discrete volumes of fluid successively. While this principle of operation is common, many different mechanical arrangements exist for putting the principle into practice. However, all versions of positive displacement meter are low-friction, low-maintenance, and long-life devices, although they do impose a small permanent pressure loss on the flowing fluid.

Low friction is especially important when measuring gas flows, and meters with special mechanical arrangements to satisfy this requirement have been developed.

The **rotary piston meter** is a common type of positive displacement meter that is used particularly for the measurement of domestic water supplies. It consists, as shown in Figure 16.9, of a slotted cylindrical piston moving inside a cylindrical working chamber that has an inlet port and an outlet port. The piston moves round the chamber such that its outer surface maintains contact with the inner surface of the chamber, and, as this happens, the piston slot slides up and down a fixed division plate in the chamber. At the start of each piston motion cycle, liquid is admitted to volume B from the inlet port. The fluid pressure causes the piston to start to rotate around the chamber, and, as this happens, liquid in volume C starts to flow out of the outlet port, and also liquid starts to flow from the inlet port into volume A. As the piston rotates further, volume B becomes shut off from the inlet port, while liquid continues to be admitted into A and pushed out of C. When the piston reaches the end point of its motion cycle, the outlet port is opened to volume B, and the liquid which has been transported round inside the piston is expelled. After this, the piston pivots about the contact point between the top of its slot and the division plate, and volume A effectively becomes volume C ready for the start of the next motion cycle. A peg on top of the piston causes a reciprocating motion of a lever attached to it. This is made to operate a counter, and the flow rate is therefore determined from the count in unit time multiplied by the quantity (fixed) of liquid transferred between the inlet and outlet ports for each motion cycle.

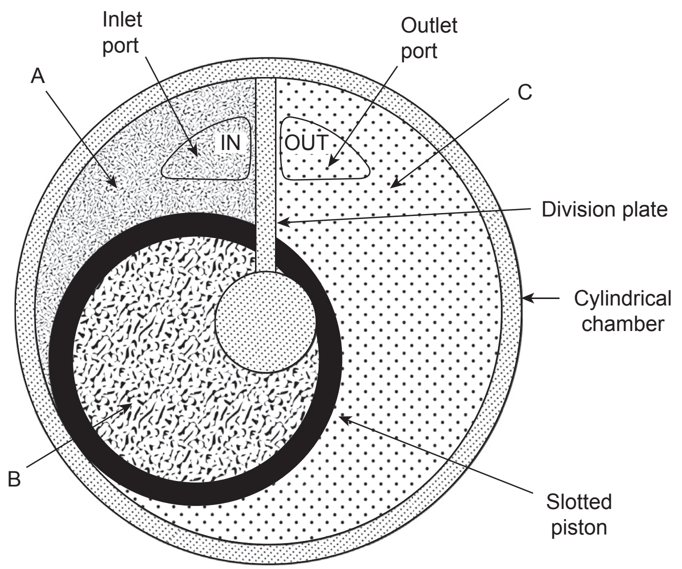

Figure 16.9
Rotary piston form of the positive displacement flowmeter.

The *nutating disk meter* is another form of positive displacement meter in which the active element is a disk inside a precision-machined chamber. Liquid flowing into the chamber causes the disk to nutate (wobble), and these nutations are translated into a rotary motion by a roller cam. Rotations are counted by a pulse transmitter that provides a measurement of the flow rate. This form of meter is noted for its ruggedness and long life. It has a typical measurement accuracy of ±1.0%. It is commonly used for water supply measurement.

The *oval gear meter* is yet another form of positive displacement meter that has two oval-shaped gear wheels. It is used particularly for measuring the flow rate of high viscosity fluids. It can also cope with measuring fluids that have variable viscosity.

16.3.4 Turbine Meters

A turbine flowmeter consists of a multibladed wheel mounted in a pipe along an axis parallel to the direction of fluid flow in the pipe, as shown in Figure 16.10. The flow of fluid past the wheel causes it to rotate at a rate that is proportional to the volume flow rate of the fluid. This rate of rotation has traditionally been measured by constructing the flowmeter such that it behaves as a variable reluctance tachogenerator. This is achieved by fabricating the turbine blades from a ferromagnetic material and placing a permanent magnet and coil inside the meter housing. A voltage pulse is induced in the coil as each blade on the turbine wheel moves past it, and if these pulses are measured by a pulse counter, the pulse frequency and hence flow rate can be deduced. In recent instruments, fiber optics are also now sometimes used to count the rotations by detecting reflections off the tip of the turbine blades.

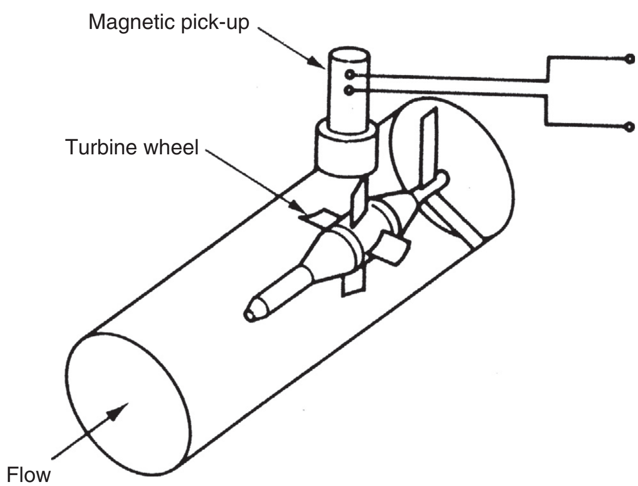

Figure 16.10
Turbine flowmeter.

Provided that the turbine wheel is mounted in low-friction bearings, measurement inaccuracy can be as low as ±0.2%. However, turbine flowmeters are less rugged and reliable than flow restriction-type instruments, and are badly affected by any particulate matter in the flowing fluid. Bearing wear is a particular problem and they also impose a permanent pressure loss on the measured system. Turbine meters are particularly prone to large errors when there is any significant second phase in the fluid measured. For instance, using a turbine meter calibrated on pure liquid to measure a liquid containing 5% air produces a 50% measurement error. As an important application of the turbine meter is in the petrochemical industries, where gas/oil mixtures are common, special procedures are being developed to avoid such large measurement errors.

Readers may find reference in manufacturers' catalogs to a *Woltmann meter*. This is a type of turbine meter that has helical blades and is used particularly for measuring high flow rates. It is also sometimes known as a *helix meter*.

Turbine meters have a similar cost and market share to positive displacement meters, and compete for many applications, particularly in the oil industry. Turbine meters are smaller and lighter than the latter and are preferred for low-viscosity, high flow measurements. However, positive displacement meters are superior in conditions of high viscosity and low flow rate.

16.3.5 Electromagnetic Flowmeters

Electromagnetic flowmeters, sometimes known just as *magnetic flowmeters*, are limited to measuring the volume flow rate of electrically conductive fluids. The typical measurement inaccuracy of around ±1% is acceptable in many applications, but the instrument is expensive both in terms of the initial purchase cost and also in running costs, mainly due to its electricity consumption. A further reason for high cost is the need for careful calibration of each instrument individually during manufacture, as there is considerable variation in the properties of the magnetic materials used.

The instrument, shown in Figure 16.11, consists of a stainless steel cylindrical tube, fitted with an insulating liner, which carries the measured fluid. Typical lining materials used are neoprene, polytetrafluoroethylene, and polyurethane. A magnetic field is created in the tube by placing mains—energized field coils either side of it, and the voltage induced in the fluid is measured by two electrodes inserted into opposite sides of the tube. The ends of these electrodes are usually flush with the inner surface of the cylinder. The electrodes are constructed from a material which is unaffected by most types of flowing fluid, such as stainless steel, platinum–iridium alloys, Hastelloy, titanium, and tantalum. In the case of the rarer metals in this list, the electrodes account for a significant part of the total instrument cost.

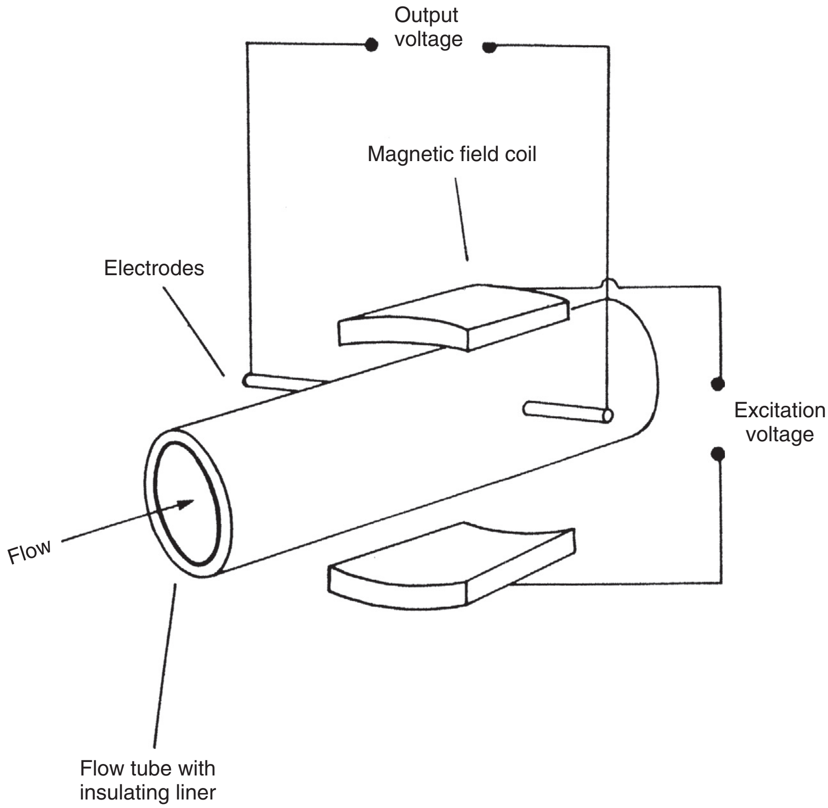

Figure 16.11
Electromagnetic flowmeter.

By Faraday's law of electromagnetic induction, the voltage E induced across a length L of the flowing fluid moving at velocity v in a magnetic field of flux density B is given by

$$E = BLv \tag{16.3}$$

L is the distance between the electrodes, which is the diameter of the tube, and B is a known constant. Hence, measurement of the voltage E induced across the electrodes allows the flow velocity v to be calculated from Eqn (16.3). Having thus calculated v, it is a simple matter to multiply v by the cross-sectional area of the tube to obtain a value for the volume flow rate. The typical voltage signal measured across the electrodes is 1 mV when the fluid flow rate is 1 m/s.

The internal diameter of electromagnetic flowmeters is normally the same as that of the rest of the flow-carrying pipework in the system. Therefore, there is no obstruction to the fluid flow and consequently no pressure loss associated with measurement. Like other forms of flowmeter, the electromagnetic type requires a minimum length of straight pipework immediately prior to the point of flow measurement in order to guarantee the accuracy of measurement, although a length equal to five pipe diameters is usually sufficient.

While the flowing fluid must be electrically conductive, the method is of use in many applications and is particularly useful for measuring the flow of slurries in which the liquid phase is electrically conductive. Corrosive fluids can be handled provided a suitable lining material is used. At the present time, electromagnetic flowmeters account for about 15% of the new flowmeters sold and this total is slowly growing. One operational problem is that the insulating lining is subject to damage when abrasive fluids are being handled, and this can give the instrument a limited life.

New developments in electromagnetic flowmeters are producing instruments that are physically smaller than before. Also, by employing better coil designs, electricity consumption is reduced. This means that battery-powered versions are now commercially available. Also, whereas conventional electromagnetic flowmeters require a minimum fluid conductivity of 10 μmho/cm^3, new versions can cope with fluid conductivities as low as 1 μmho/cm^3.

16.3.6 Vortex-Shedding Flowmeters

The vortex-shedding flowmeter is used as an alternative to traditional differential pressure meters in many applications. The operating principle of the instrument is based on the natural phenomenon of vortex shedding, created by placing an unstreamlined obstacle (known as a bluff body) in a fluid-carrying pipe, as indicated in Figure 16.12. When fluid flows past the obstacle, boundary layers of viscous, slow moving fluid are formed along

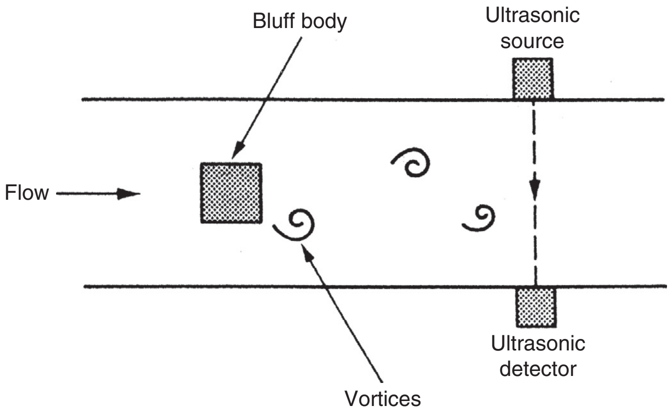

Figure 16.12
Vortex-shedding flowmeter.

the outer surface. Because the obstacle is not streamlined, the flow cannot follow the contours of the body on the downstream side, and the separate layers become detached and roll into eddies or vortices in the low-pressure region behind the obstacle. The shedding frequency of these alternately shed vortices is proportional to the fluid velocity past the body. Various thermal, magnetic, ultrasonic, and capacitive vortex detection techniques are employed in different instruments.

Such instruments have no moving parts, operate over a wide flow range, have small power consumption, require little maintenance, and have a similar cost to measurement using an orifice plate. They can measure both liquid and gas flows and a common inaccuracy value quoted is $\pm1\%$ of full-scale reading, though this can be seriously downgraded in the presence of flow disturbances upstream of the measurement point and a straight run of pipe before the measurement point of 50 pipe diameters is recommended. Another problem with the instrument is its susceptibility to pipe vibrations, although new designs are becoming available which have a better immunity to such vibrations.

16.3.7 Ultrasonic Flowmeters

The ultrasonic technique of volume flow rate measurement is, like the magnetic flowmeter, a noninvasive method. It is not restricted to conductive fluids, however, and is particularly useful for measuring the flow of corrosive fluids and slurries. Besides its high reliability and low maintenance requirements, a further advantage of an ultrasonic flowmeter over an electromagnetic flowmeter is that the instrument can be clamped externally onto existing pipework rather than being inserted as an integral part of the flow line. As the procedure of breaking into a pipeline to insert a flowmeter can be as expensive as the cost of the flowmeter itself, the ultrasonic flowmeter has enormous cost advantages. Its clamp-on mode of operation also has significant safety advantages in avoiding the possibility of personnel installing flowmeters coming into contact with hazardous fluids such as poisonous, radioactive, flammable, or explosive ones. Also, any contamination of the fluid being measured (e.g., food substances and drugs) is avoided. Ultrasonic meters are still less common than differential pressure or electromagnetic flowmeters, though usage continues to expand year by year.

Two different types of ultrasonic flowmeter exist which employ distinct technologies, one based on Doppler shift and the other on transit time. In the past, the existence of these alternative technologies has not always been readily understood, and has resulted in ultrasonic technology being rejected entirely when one of these two forms has been found to be unsatisfactory in a particular application. This is unfortunate, because the two technologies have distinct characteristics and areas of application, and many situations exist where one form is very suitable and the other not suitable. To reject both, having only tried out one, is therefore a serious mistake. Recently, ultrasonic flowmeters have become available which combine both Doppler shift and transit time technologies.

Particular care has to be taken to ensure a stable flow profile in ultrasonic flowmeter applications. It is usual to increase the normal specification of the minimum length of straight pipe run prior to the point of measurement, expressed as a number of pipe diameters, from a value of 10 up to 20 or in some cases even 50 diameters. Analysis of the reasons for poor performance in many instances of ultrasonic flowmeter application has shown failure to meet this stable flow-profile requirement to be a significant factor.

Doppler shift ultrasonic flowmeter

The principle of operation of the Doppler shift flowmeter is shown in Figure 16.13. A fundamental requirement of these instruments is the presence of scattering elements within the flowing fluid, which deflect the ultrasonic energy output from the transmitter such that it enters the receiver. These can be provided by either solid particles, gas bubbles, or eddies in the flowing fluid. The scattering elements cause a frequency shift between the transmitted and reflected ultrasonic energy, and measurement of this shift enables the fluid velocity to be inferred.

The instrument consists essentially of an ultrasonic transmitter—receiver pair clamped onto the outside wall of a fluid-carrying vessel. Ultrasonic energy consists of a train of short bursts of sinusoidal waveforms at a frequency between 0.5 and 20 MHz. This frequency

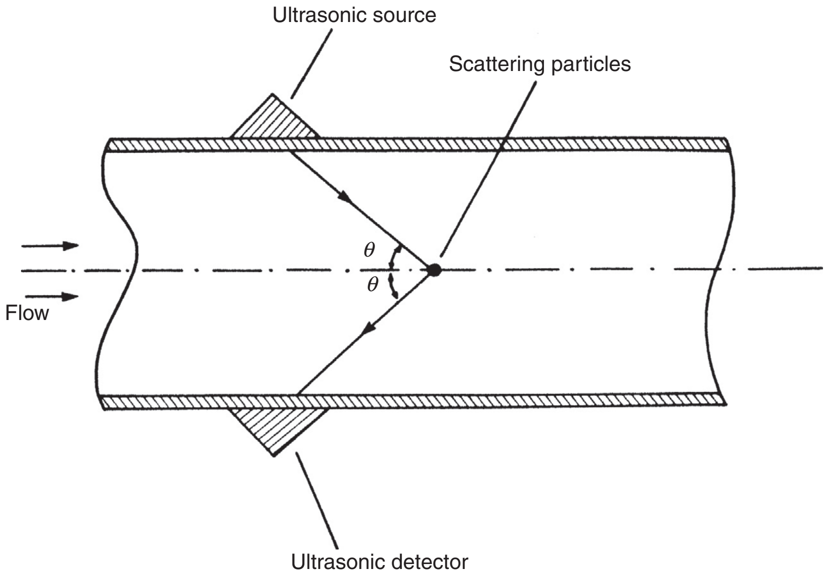

Figure 16.13
Doppler shift ultrasonic flowmeter.

range is described as ultrasonic because it is outside the range of human hearing. The flow velocity v is given by

$$v = \frac{c(f_t - f_r)}{2f_t \cos(\theta)} \tag{16.4}$$

where f_t and f_r are the frequencies of the transmitted and received ultrasonic waves respectively, c is the velocity of sound in the fluid being measured, and θ is the angle that the incident and reflected energy waves make with the axis of flow in the pipe. Volume flow rate is then readily calculated by multiplying the measured flow velocity by the cross-sectional area of the fluid-carrying pipe.

The electronics involved in Doppler shift flowmeters is relatively simple and therefore cheap. Ultrasonic transmitters and receivers are also relatively inexpensive, being based on piezoelectric oscillator technology. Therefore, as all of its components are cheap, the Doppler shift flowmeter itself is inexpensive. The measurement accuracy obtained depends on many factors such as the flow profile, the constancy of pipe wall thickness, the number, size and spatial distribution of scatterers, and the accuracy with which the speed of sound in the fluid is known. Consequently, accurate measurement can only be achieved by the tedious procedure of carefully calibrating the instrument in each particular flow measurement application. Otherwise, measurement errors can approach $\pm 10\%$ of the reading, and for this reason Doppler shift flowmeters are often used merely as flow indicators, rather than for accurate quantification of the volume flow rate.

Versions are now available which are being fitted inside the flow pipe, flush with its inner surface. This overcomes the problem of variable pipe thickness, and an inaccuracy level as small as $\pm 0.5\%$ is claimed for such devices. Other recent developments are the use of multiple path ultrasonic flowmeters that use an array of ultrasonic elements to obtain an average velocity measurement. This substantially reduces the error due to nonuniform flow profiles but there is a substantial cost penalty involved in such devices.

Transit time ultrasonic flowmeter

The transit time ultrasonic flowmeter is an instrument that is designed for measuring the volume flow rate in clean liquids or gases. It consists of a pair of ultrasonic transducers mounted along an axis aligned at an angle θ with respect to the fluid flow axis, as shown in Figure 16.14.

Each transducer consists of a transmitter—receiver pair, with the transmitter emitting ultrasonic energy that travels across to the receiver on the opposite side of the pipe. These ultrasonic elements are normally piezoelectric oscillators of the same type as used in Doppler shift flowmeters. Fluid flowing in the pipe causes a time difference between the transit times of the beams traveling upstream and downstream, and measurement of this

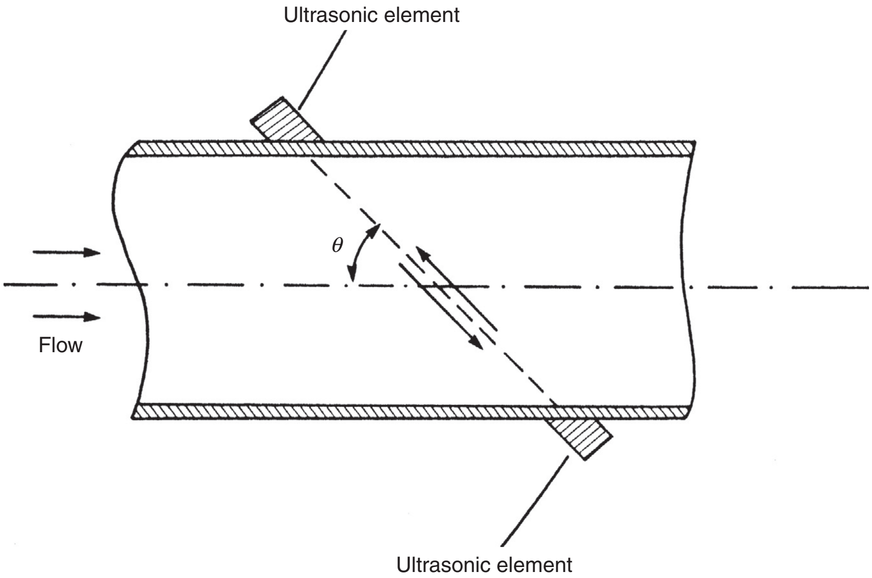

Figure 16.14
Transit time ultrasonic flowmeter.

difference allows the flow velocity to be calculated. The typical magnitude of this time difference is 100 ns in a total transit time of 100 μs, and high-precision electronics are therefore needed to measure the difference. There are three distinct ways of measuring the time shift. These are direct measurement, conversion to a phase change, and conversion to a frequency change. The third of these options is particularly attractive, as it obviates the need to measure the speed of sound in the measured fluid as required by the first two methods. A scheme applying this third option is shown in Figure 16.15. This also multiplexes the

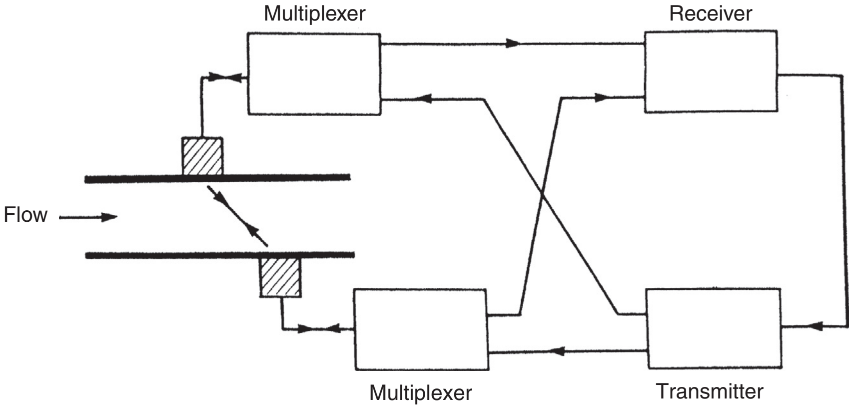

Figure 16.15
Transit time measurement system.

transmitting and receiving functions, so that only one ultrasonic element is needed in each transducer. The forward and backward transit times across the pipe, T_f and T_b, are given by

$$T_f = \frac{L}{c + v\cos(\theta)}; \quad T_b = \frac{L}{c - v\cos(\theta)}$$

where c is the velocity of sound in the fluid, v is the flow velocity, L is the distance between the ultrasonic transmitter and receiver, and θ is the angle of the ultrasonic beam with respect to the fluid flow axis.

The time difference δT is given by

$$\delta T = T_b - T_f = \frac{2vL\cos(\theta)}{c^2 - v^2\cos^2(\theta)}$$

This requires knowledge of c before it can be solved. However, a solution can be found much more simply if the receipt of a pulse is used to trigger the transmission of the next ultrasonic energy pulse. Then, the frequencies of the forward and backward pulse trains are given by

$$F_f = \frac{1}{T_f} = \frac{c - v\cos(\theta)}{L}; \quad F_b = \frac{1}{T_b} = \frac{c + v\cos(\theta)}{L}$$

If the two frequency signals are now multiplied together, the resulting beat frequency is given by

$$\delta F = F_b - F_f = \frac{2v\cos(\theta)}{L}$$

c has now been eliminated and v can be calculated from a measurement of δF as

$$v = \frac{L\delta F}{2\cos(\theta)}$$

This is often known as the *sing around flowmeter.*

Transit time flowmeters are of more general use than Doppler shift flowmeters, particularly where the pipe diameter involved is large and hence the transit time is consequently sufficiently large to be measured with reasonable accuracy. It is possible then to reduce the inaccuracy value down to $\pm 0.5\%$. However, the instrument costs more than a Doppler shift flowmeter because of the greater complexity of the electronics needed to make accurate transit time measurements.

Combined Doppler shift/transit time flowmeters

Recently, some manufacturers have developed ultrasonic flowmeters that use a combination of Doppler shift and transit time. The exact mechanism by which these work is rarely, if ever, disclosed, since manufacturers wish to protect the details from competitors. However, details of various forms of combined Doppler shift/transit time measurement techniques are filed in patent offices.

16.3.8 Other Types of Flowmeter for Measuring Volume Flow Rate

Vane meter: This consists of a spring-loaded, hinged flap mounted at right angles to the direction of fluid flow in the fluid-carrying pipe. The original form of this was known as a *gate meter*, in which the movement of the flap was measured by connecting it to a pointer outside the pipe that moved against a graduated scale. The major difficulty with the gate meter was in preventing leaks at the hinge point. The vane meter avoids this difficulty by measuring the deflection of the flap by a potentiometer mounted inside the fluid-carrying pipe. It is typically used to measure airflow within automotive fuel injection systems. Another similar device is the *target meter*. This consists of a circular disc-shaped flap in the pipe. Fluid flow rate is inferred from the force exerted on the disc measured by strain gauges bonded to it. This meter is very useful for measuring the flow of dilute slurries but it does not find wide application elsewhere as it has a relatively high cost. Measurement uncertainty in all of these types of meter varies between 1% and 5% according to cost and design of each instrument.

Jet meter: These come in two forms, the single jet meter and the multiple jet meter. In the first, the flow is diverted into a single jet which impinges on the radial vanes of an impeller. The multiple jet form diverts the flow into multiple jets that are arranged at equal angles around an impeller that is mounted on a horizontal axis.

Paddle wheel meter: This is a variation of the single jet meter in which the impeller only projects partially into the flowing fluid.

Jet meters are commonly used in water supply meters.

Pelton wheel flowmeter: This uses a similar mechanical arrangement to the old-fashioned water wheels that were used for power generation at the time of the industrial revolution. The flowing fluid is directed by a jet onto the blades of the flowmeter wheel, and the flow rate is determined from the rate of rotation of the wheel. This type of flowmeter is used to measure the flow rate of a diverse range of materials including acids, aggressive chemicals, and hot fats at both low and high flow rates. Special versions can measure very small flow rates down to 3 ml/min.

Laser Doppler flowmeter: This instrument gives direct measurements of flow velocity for liquids containing suspended particles flowing in a pipe. Light from a laser is focused by an optical system to a point in the flow, with fiber optic cables being commonly used to transmit the light. The movement of particles in the flowing fluid causes a Doppler shift of the scattered light and produces a signal in a photodetector that is related to the fluid velocity. A very wide range of flow velocities between 10 μm/s and 105 m/s can be measured by this technique.

Sufficient particles for satisfactory operation are normally present naturally in most liquid and gaseous fluids, and the introduction of artificial particles is rarely needed. The technique is advantageous in measuring flow velocity directly rather than inferring it from a pressure difference. It also causes no interruption in the flow and, as the instrument can be made very small, it can measure velocity in confined areas. One limitation is that it measures local flow velocity in the vicinity of the focal point of the light beam, which can lead to large errors in the estimation of mean volume flow rate if the flow profile is not uniform. However, this limitation can be used constructively in applications of the instrument where the flow profile across the cross section of a pipe is determined by measuring the velocity at a succession of points.

The final comment on this instrument has to be that, although it could potentially be used in many applications, it has competition from many other types of instruments that offer similar performance at lower cost. Its main application at the present time is in measuring blood flow in medical applications.

Thermal anemometers: Thermal anemometry was first used in the *hot-wire anemometer* to measure the volume flow rate of gases flowing in pipes. The hot-wire anemometer consists of a piece of thin (typical diameter of 5 μm), electrically heated wire (usually tungsten, platinum, or a platinum–iridium alloy) that is inserted into the gas flow. The flowing gas has a cooling effect on the wire which reduces its resistance. Measurement of the resistance change (usually by a bridge circuit) allows the volume flow rate of the gas to be calculated. Unfortunately, the device is not robust because of the very small diameter of the wire used in its construction. However, it has a very fast speed of response, which makes it an ideal measurement device in conditions where the flow velocity is changing. It is also insensitive to the direction of gas flow, making it a very useful measuring device in conditions of turbulent flow. Recently, more robust devices have been made by using a thin metal film instead of a wire. In this form, the device is known as a *hot-film anemometer*. Typically, the film is platinum and it is deposited on a quartz probe of typical diameter 0.05 mm. The increased robustness means that the hot-film anemometer is also used to measure the flow rate of liquids such as water.

Coriolis meter: While the Coriolis meter is primarily intended to be a mass flow measuring instrument, it can also be used to measure volume flow rate when high measurement accuracy is required. However, its high cost means that alternative instruments are normally used for measuring volume flow rate.

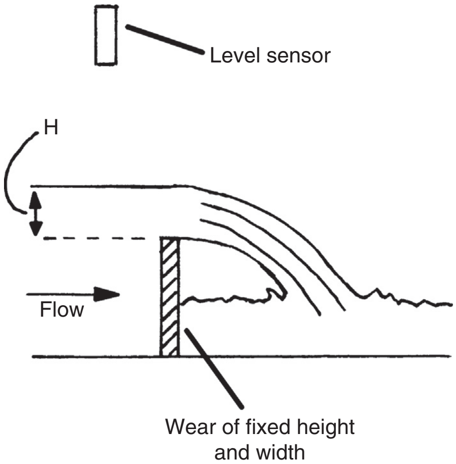

Figure 16.16
Open channel flowmeter.

16.3.9 Open Channel Flowmeters

Open channel flowmeters measure the flow of liquids in open channels and are particularly relevant to measuring the flow of water in rivers as part of environmental management schemes. The normal procedure is to build a weir or flume of constant width across the flow and measure the velocity of flow and the height of liquid immediately before the weir or flume with an ultrasonic or radar level sensor, as shown in Figure 16.16. The volume flow rate can then be calculated from this measured height.

As an alternative to building a weir or flume, electromagnetic flowmeters up to 180-mm wide are available that can be placed across the channel to measure the flow velocity provided the flowing liquid is conductive. If the channel is wider than 180 mm, two or more electromagnetic meters can be placed side by side. Apart from measuring the flow velocity in this way, the height of the flowing liquid must also be measured, and the width of the channel must also be known in order to calculate the volume flow rate.

As a third alternative, ultrasonic flowmeters are also used to measure flow velocity in conjunction with a device to measure the liquid depth.

16.4 Intelligent Flowmeters

All the usual benefits associated with intelligent instruments are applicable to most types of flowmeter. Indeed, all types of mass flowmeter routinely have intelligence as an integral part of the instrument. For volume flow rate measurement, intelligent differential pressure measuring instruments can be used to good effect in conjunction with obstruction-type flow transducers. One immediate benefit of this in the case of the commonest flow-restriction device, the orifice plate, is to extend the lowest flow measurable with acceptable accuracy down to 20% of the maximum flow value. In positive displacement meters, intelligence allows compensation for thermal expansion of meter components and temperature-induced viscosity changes. Correction for variations in flow pressure is also provided for. Intelligent electromagnetic flowmeters are also available, and these have a self-diagnosis and self-adjustment capability. The usable instrument range is typically from 3% to 100% of the full-scale reading and the quoted maximum inaccuracy is $\pm$0.5%. It is also normal to include a nonvolatile memory to protect constants used for correcting for modifying inputs, etc., against power supply failures. Intelligent turbine meters are able to detect their own bearing wear and also report deviations from initial calibration due to blade damage, etc. Some versions also have self-adjustment capability.

The ability to carry out digital signal processing has also led to the emergence of the *cross-correlation ultrasonic flowmeter*. This is a variant of the transit time form of ultrasonic flowmeter in which a series of ultrasonic signals are injected into the flowing liquid. The ultrasonic receiver stores the echo pattern from each input signal and then cross-correlation techniques are used to produce a map of the profile of the water flow in different layers. Thus, the instrument provides information on the profile of the flow rate across the cross section of the pipe rather than just giving a measurement of the mean flow rate in the pipe.

The trend is now moving toward total flow computers which can process inputs from almost any type of transducer. Such devices allow user input of parameters like specific gravity, fluid density, viscosity, pipe diameters, thermal expansion coefficients, discharge coefficients, etc. Auxiliary inputs from temperature transducers are also catered for. After processing the raw flow transducer output with this additional data, flow computers are able to produce measurements of flow to a very high degree of accuracy.

16.5 Choice between Flowmeters for Particular Applications

The first question to answer in specifying a suitable flowmeter for a given application is whether the flowing material is a solid, liquid, or gas. If the material is a solid (powders or granular particles), the only option is to measure the mass flow rate using some form of mass flowmeter. However, if the flowing material is in liquid or gaseous form, the flow can be measured either as the mass flow rate or as the volume flow rate. Of the two, measurement of the flow in terms of the mass flow rate is usually preferred if there is a requirement for high measurement accuracy.

If the flowing material is a solid, the only technique available to measure the flow rate is a conveyor-based method. The standard way to do this is to measure the mass flowing in unit time. However, an alternative nuclear mass flow sensor is now available, as discussed in Section 16.2.1.

If the material flowing is in liquid or gaseous form, there are a large number of factors to be considered when specifying a flowmeter for a particular application. These include the temperature and pressure of the fluid, its density, viscosity, chemical properties, and abrasiveness, whether it contains particles, whether it is a liquid or gas, etc. This narrows the field to a subset of instruments that are physically capable of making the measurement. Next, the required performance factors of accuracy, rangeability, acceptable pressure drop, output signal characteristics, reliability, and service life must be considered. Accuracy requirements vary widely across different applications, with measurement uncertainty of $\pm 5\%$ being acceptable in some and less than $\pm 0.5\%$ being demanded in others. Finally, the economic viability must be assessed and this must take an account not only of purchase cost, but also of reliability, installation difficulties, maintenance requirements, and service life.

Where only a visual indication of fluid flow rate is needed, the variable area meter is popular. Where a flow measurement in the form of an electrical signal is required, the choice of available instruments is very large. The orifice plate is used extremely commonly for such purposes and accounts for almost 50% of the instruments currently in use in industry. Other forms of differential pressure meter and electromagnetic flowmeters are used in significant numbers. Currently, there is a trend away from rotating devices such as turbine meters and positive displacement meters. At the same time, usage of ultrasonic and vortex meters is expanding. Where high accuracy flow measurement is needed, mass flow rate devices like the Coriolis meter and thermal mass flowmeter (including MEMS devices) are commonly used.

16.6 Calibration of Flowmeters

The first consideration in choosing a suitable way to calibrate flow measuring instruments is to establish exactly what accuracy level is needed so that the calibration system instituted does not cost more than necessary. In some cases, such as handling valuable fluids or where there are legal requirements as in petrol pumps, high accuracy levels (e.g., error $\leq 0.1\%$) are necessary and the expensive procedures necessary to achieve are justified. However, in other situations, such as in measuring additives to the main stream in a process plant, only low levels of accuracy are needed (e.g., error $\approx 5\%$ is acceptable) and relatively cheap calibration procedures are sufficient.

The accuracy of flow measurement is greatly affected by the flow conditions and characteristics of the flowing fluid. Therefore, wherever possible, process flow measuring instruments are calibrated on-site in their normal measuring position. This ensures that calibration is performed in the actual flow conditions, which are difficult or impossible to reproduce exactly in a laboratory. To ensure the validity of such calibration, it is also a normal practice to repeat flow calibration checks until the same reading is obtained in two consecutive tests. However, it has been suggested that even these precautions are inadequate and that statistical procedures are needed.

If on-site calibration is not feasible or is not accurate enough, the only alternative is to send the instrument away for calibration using special equipment provided by instrument manufacturers or other specialist calibration companies. However, this is usually an expensive option. Furthermore, the calibration facility does not replicate the normal operating conditions of the meter tested, and appropriate compensation for the differences between calibration conditions and normal use conditions must be applied.

The equipment and procedures used for calibration depend on whether mass, liquid, or gaseous flows are being measured. Therefore, separate sections are devoted to each of these cases. It must also be stressed that all calibration procedures mentioned in the following paragraphs in respect of fluid flow only refer to flows of single-phase fluids (i.e., liquids or gases). Where a second or third phase is present, calibration is much more difficult and specialist advice should be sought from the manufacturer of the instrument used for measurement.

16.6.1 Calibration Equipment and Procedures for Mass Flow Measuring Instruments

Where the conveyor method is used for measuring the mass flow of solids in the form of particles or powders, both mass and velocity measuring instruments are involved. Suitable calibration techniques for each of these are discussed in later chapters.

In the case of the Coriolis and thermal mass flowmeters, the usual method of calibrating these while in situ in their normal measurement position is to provide a diversion valve after the meter. During calibration procedures, the valve is opened for a measured time period to allow some of the fluid to flow into a container that is subsequently weighed. Alternatively, the meter can be removed for calibration using special test rigs that are normally provided by the instrument manufacturer.

16.6.2 Calibration Equipment and Procedures for Instruments Measuring the Volume Flow Rate of Liquids

Calibrated tank

Probably the simplest piece of equipment available for calibrating instruments measuring liquid flow rates is the calibrated tank. This consists of a cylindrical vessel, as shown in Figure 16.17, with conical ends that facilitate draining and cleaning of the tank. A *sight tube* with a graduated scale is placed alongside the final, upper, cylindrical part of the tank

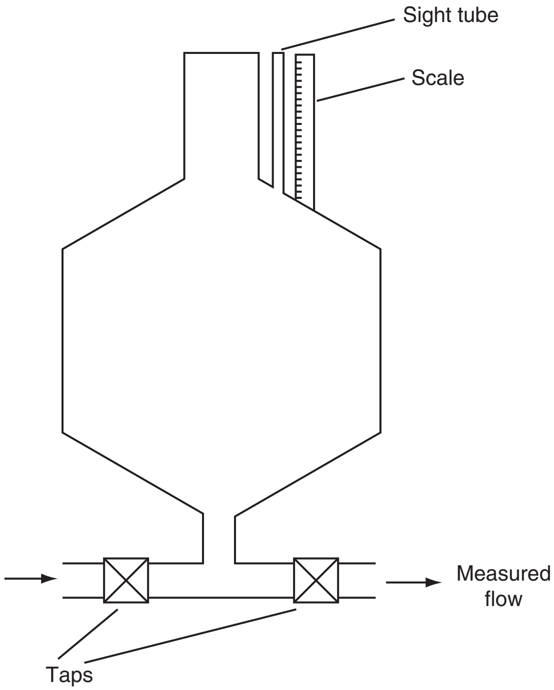

Figure 16.17
Calibrated tank.

and this allows the volume of liquid in the tank to be measured accurately. Flow rate calibration is performed by measuring the time taken, starting from an empty tank, for a given volume of liquid to flow into the vessel.

Because the calibration procedure starts and ends in zero flow conditions, it is not suitable for calibrating instruments which are affected by flow acceleration and deceleration characteristics. This therefore excludes instruments like differential pressure meters (orifice plate, flow nozzle, Venturi, Dall flow tube, Pitot tube), turbine flowmeters, and vortex-shedding flowmeters. The technique is further limited to the calibration of low-viscosity liquid flows, although lining the tank with an epoxy coating can allow the system to cope with somewhat higher viscosities. The limiting factor in this case is the drainage characteristics of the tank, which must be such that the residue liquid left after draining has an insufficient volume to affect the accuracy of the next calibration.

Pipe prover

The commonest form of pipe prover is the bidirectional type, shown in Figure 16.18, which consists of a U-shaped tube of metal of accurately known cross section. The purpose of the U-bend is to give a long flow path within a compact spatial volume. Alternative versions with more than one U-bend also exist to cater for situations where an

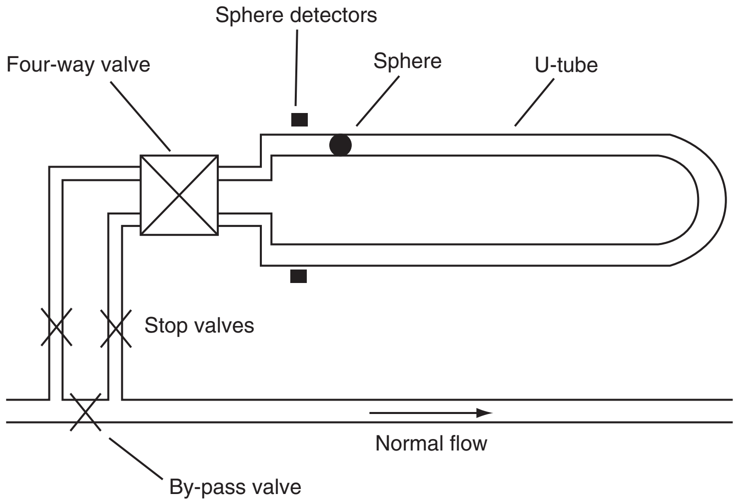

Figure 16.18
Bidirectional pipe prover.

even longer flow path is required. Inside the tube is a hollow, inflatable sphere which is filled with water until its diameter is about 2% larger than that of the tube. As such, the sphere forms a seal with the sides of the tube and acts as a piston. The prover is connected into the existing fluid-carrying pipe network via tappings either side of a bypass valve. A four-way valve at the start of the U-tube allows fluid to be directed in either direction around it. Calibration is performed by diverting flow into the prover and measuring the time taken for the sphere to travel between two detectors in the tube. The detectors are normally of an electromechanical, plunger type.

Unidirectional versions of the above also exist in which fluid only flows in one direction around the tube. A special handling valve has to be provided to return the sphere to the starting point after each calibration, but the absence of a four-way flow control valve makes such devices significantly cheaper than bidirectional types.

Pipe provers are particularly suited to the calibration of pressure measuring instruments which have a pulse type of output, such as turbine meters. In such cases, the detector switches in the tube can be made to gate the instrument's output pulse counter. This enables not only the basic instrument to be calibrated, but also the ancillary electronics within it at the same time. The inaccuracy level of such provers can be as low as ±0.1%. This level of accuracy is maintained for high fluid viscosity levels and also at very high flow rates. Even higher accuracy is provided by an alternative form of prover which consists of a long, straight metal tube containing a metal piston. However, such devices are more expensive than the other types discussed above and their large space requirements also often cause great difficulties.

Compact prover

The compact prover has an identical operating principle to that of the other pipe provers described above but occupies a much smaller spatial volume. It is therefore used extensively in situations where there is insufficient room to use a larger prover. Many different designs of compact prover exist, operating both in the unidirectional and bidirectional modes, and one such design is shown in Figure 16.19. Common features of compact provers are an accurately machined cylinder containing a metal piston which is driven between two reference marks by the flowing fluid. The instants at which the reference marks are passed are detected by switches, of optical form in the case of the version shown in Figure 16.19. Provision has to be made within these instruments for returning the piston back to the starting point after each calibration and a hydraulic system is commonly used for this. Again, measuring the piston traverse time is made easier if the switches can be made to gate a pulse train, and therefore compact provers are also most suited to instruments having a pulse type output such as turbine meters. Measurement uncertainty levels down to ±0.1% are possible.

The main technical difficulty in compact provers is measuring the traverse time, which can be as small as 1 s. The pulse count from a turbine meter in this time would typically be only about 100, making the possible measurement error 1%. To overcome this problem, electronic pulse interpolation techniques have been developed which can count fractions of pulses.

Positive displacement meter

High-quality versions of the positive displacement flowmeter can be used as a reference standard in flowmeter calibration. The general principles of these were explained in Section 16.3.3. Such special calibration versions give measurement inaccuracy levels down to ±0.2%.

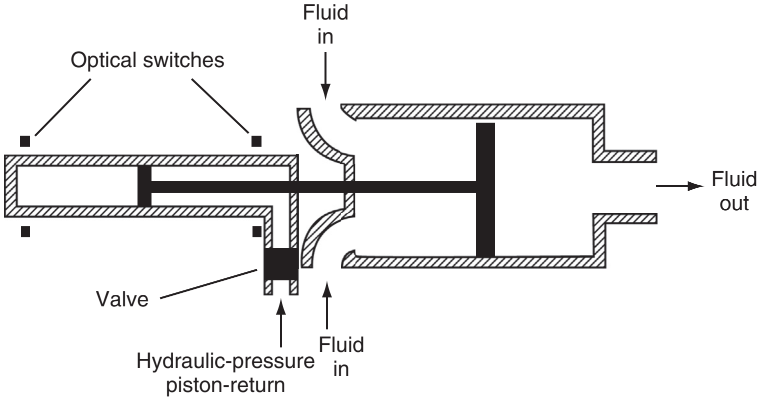

Figure 16.19
Compact prover.

Gravimetric method

A variation on the principle of measuring the volume of liquid flowing in a given time is to weigh the quantity of fluid flowing in a given time. Apart from its applicability to a wider range of instruments, this technique is not limited to low viscosity fluids as any residual fluid in the tank before calibration will be detected by the load cells and therefore compensated for. In the simplest implementation of this system, fluid is allowed to flow for a measured length of time into a tank resting on load cells. As before, the stop–start mode of fluid flow makes this method unsuitable for calibrating differential pressure, turbine, and vortex-shedding flowmeters. It is also unsuitable for measuring high flow rates because of the difficulty in bringing the fluid to rest. These restrictions can be overcome by directing the flowing fluid into the tank via diverter valves. In this alternative, it is important that the timing system be carefully synchronized with the operation of the diverter valves.

All versions of gravimetric calibration equipment are less robust than volumetric types and so on-site use is not recommended.

Orifice plate

A flow line equipped with a certified orifice plate is sometimes used as a reference standard in flow calibration, especially for high flow rates through large bore pipes. While measurement uncertainty is of the order of $\pm 1\%$ at best, this is adequate for calibrating many flow measuring instruments.

Turbine meter

Turbine meters are also used as a reference standard for testing flowmeters. Their main application, as for orifice plates, is in calibrating high flow rates through large bore pipes. Measurement uncertainty down to $\pm 0.2\%$ is attainable.

16.6.3 Calibration Equipment and Procedures for Instruments Measuring the Volume Flow Rate of Gases

Calibration of gaseous flows poses considerable difficulties compared with calibrating liquid flows. These problems include the lower density of gases, their compressibility, and the difficulty in establishing a suitable liquid/air interface as utilized in many liquid flow measurement systems.

In consequence, the main methods of calibrating gaseous flows, as described below, are small in number. Certain other specialized techniques, including the gravimetric method and the pressure–volume–temperature method, are also available. These provide primary reference standards for gaseous flow calibration with measurement uncertainty down to ±0.3%. However, the expense of the equipment involved is such that it is usually only available in national standards laboratories.

Bell prover

The bell prover consists of a hollow, inverted, metal cylinder suspended over a bath containing light oil, as shown in Figure 16.20. The air volume in the cylinder above the oil is connected, via a tube and a valve, to the flowmeter being calibrated. An airflow through the meter is created by allowing the cylinder to fall downward into the bath, thus displacing the air contained within it. The flow rate, which is measured by timing the rate of fall of the cylinder, can be adjusted by changing the value of counterweights attached via a low-friction pulley system to the cylinder. This is essentially laboratory-only equipment and therefore on-site calibration is not possible.

Positive displacement meter

As for liquid flow calibration, positive displacement flowmeters can be used for the calibration of gaseous flows with inaccuracy levels down to ±F0.2%.

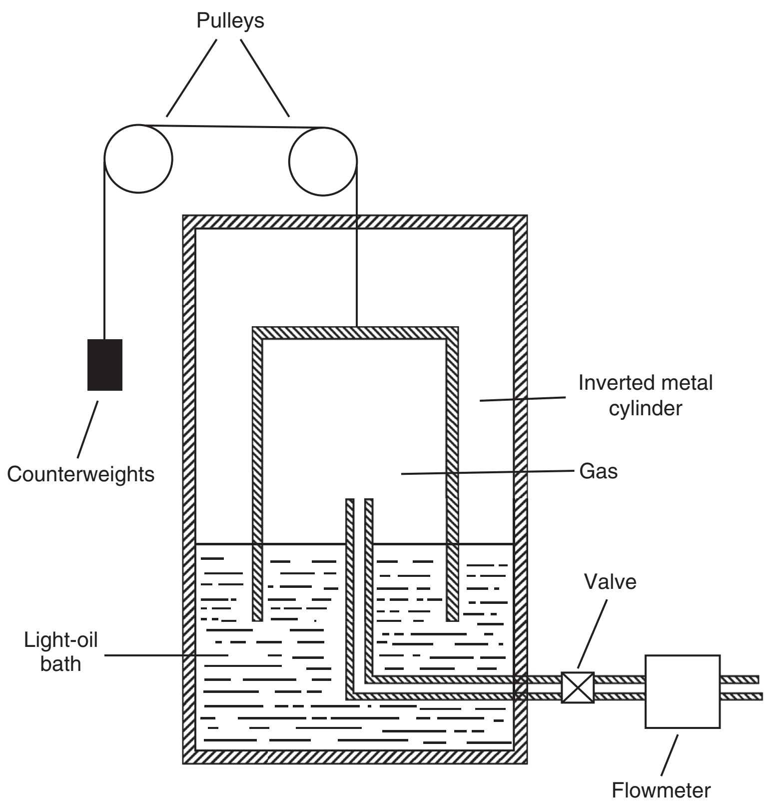

Figure 16.20
Bell prover.

Compact prover

Compact provers of the type used for calibrating liquid flows are unsuitable for application to gaseous flows. However, special designs of compact prover are being developed for gaseous flows, and hence such devices may find application in gaseous flow calibration in the future.

16.6.4 Reference Standards

Traceability of flow rate calibration to fundamental standards is provided for reference to primary standards of the separate quantities that flow rate is calculated from. Mass measurements are calibrated by comparison with a copy of the international standard kilogram (see Chapter 18) and time is calibrated by reference to a cesium resonator standard. Volume measurements are calibrated against standard reference volumes which are themselves calibrated gravimetrically using a mass measurement system traceable to the standard kilogram.

16.7 Summary

We started this chapter off by observing that flow rate could be measured either as mass flow rate or volume flow rate. We also observed that the material being measured could be in solid, liquid, or gaseous form. In the case of solids, we quickly found that this could only be measured in terms of the mass flow rate. However, in the case of liquids and gases, we found that we have the option of measuring either the mass flow rate or the volume flow rate. Of these two alternatives, we observed that mass flow measurement was the more accurate.

Before proceeding to look at flow measurement in detail, we had a brief look at the differences between laminar flow and turbulent flow. This taught us that the flow rate was difficult to measure in turbulent flow conditions and even in laminar flow at high velocities. Therefore, as far as possible, the measurement was made at a point in the flow where the flow was at least approximately laminar and the flow velocity was as small as possible.

This allowed us to look at flow measuring instruments in more detail. We start with mass flow and observed that this could be measured in one of the three ways, conveyor-based methods, the Coriolis flowmeter, and the thermal mass flowmeter. We examined the mode of operation of each of these and made some comments about their applicability. In the case of the thermal mass flowmeter, we also looked at MEMS versions of this.

Moving on, we then started to look at volume flow rate measurement and worked progressively through a large number of different instruments that can be used. First, we looked at obstruction devices. These are placed in a fluid-carrying pipe and cause a pressure difference across the obstruction which is a function of the flow rate of the fluid. Various obstruction devices were discussed, from the commonly used cheap but less accurate orifice plate to more expensive but more accurate devices like the Venturi tube, the flow nozzle, and the Dall flow tube.

After looking at flow obstruction devices, we looked at a number of other instruments for measuring volume flow rate of fluids flowing in pipes including the variable area flowmeter, positive displacement flowmeter, turbine flowmeter, electromagnetic flowmeter, vortex-shedding flowmeter, and finally ultrasonic flowmeters in both transit time and Doppler shift forms. We also looked briefly at several other devices including gate-type meters, the laser Doppler flowmeter, and the thermal anemometer. Finally, we also had a brief look at measuring fluid flow in open channels and observed three ways of doing this.

We rounded off our discussion of flow measurement by looking at intelligent devices. We observed that these bring the usual benefits associated with intelligent instruments including improved measurement accuracy and extended measurement range, with facilities for self-diagnosis and self-adjustment also being common. This lead on to some discussion about the most appropriate instrument to use in particular flow measurement situations and applications out of all the instruments covered in the chapter.

We then concluded the chapter by considering the subject of flowmeter calibration. These calibration methods were considered in three parts. First, we looked at the calibration of instruments measuring mass flow. Second, we looked at the calibration of instruments measuring the volume flow rate of liquids. Finally, we looked at the calibration of instruments measuring the volume flow rate of gases.

16.8 Problems

16.1 Name and discuss three different kinds of instruments that are used for measuring the mass flow rate of substances (mass flowing in unit time).

16.2 Instruments to measure the volume flow rate of fluids (volume flowing in unit time) can be divided into a number of different types. Explain what these different types are and briefly discuss how instruments in each class work, using sketches of instruments as appropriate.

16.3 What is a Coriolis meter? What is it used for and how does it work?

16.4 Name five different kinds of differential pressure meter. Briefly discuss how each one works and explain the main advantages and disadvantages of each type.

16.5 Explain how each of the following works, summarize their characteristics and give typical applications: Rotameter, Rotary piston meter.

16.6 How does an electromagnetic flowmeter work and what is it typically used for?

16.7 Discuss the mode of operation and applications of each of the following: Turbine meter, Vortex-shedding flowmeter.

16.8 What are the two main types of ultrasonic flowmeter? Discuss the mode of operation of each.

16.9 How does each of the following work and what are they particularly useful for: Vane meter, Jet meter, Pelton wheel meter, Laser Doppler flowmeter, Thermal anemometer.

16.10 What is an open channel flowmeter? Draw a sketch of one and explain how it works.

16.11 What instruments, special equipment, and procedures are used in the calibration of flowmeters that are used for measuring the flow of single-phase liquids?

16.12 What instruments, special equipment, and procedures are used in the calibration of flowmeters that are used for measuring the flow of single-phase gases?