



MEASUREMENT OF VELOCITY

Definition: Linear Velocity is distance/time (mm/time, cm/time, m/time, km/hr)

$$v = \frac{s}{t}$$

Principles of fluid mechanics:

Shear stress and viscosity

There are three states of matter: solid, liquid and gas. Liquids and gases are different in many respects but behave in the same way under the action of a deforming force. Liquids and gases, i.e. fluids, flow under the action of a deforming force, whereas a solid retains its shape. The effect is illustrated in Figure 8.1(a), which shows the effect of a shear force F on a rectangular block. The corresponding shear stress τ is the force per unit area F/A , where A is the area of the base of the block.

The effect of τ is to deform the block as shown, and the resulting *shear strain* is quantified by the angle ϕ . In a solid ϕ will be constant with time and of magnitude proportional to τ . In a fluid ϕ will increase with time and the fluid will flow.

Figure 8.1(b) shows a fluid flowing over a solid boundary, e.g. a flat plate. The fluid in contact with the plate surface at $y = 0$ has zero velocity. As we move away from the plate, i.e. as y increases, the velocity v of the layers increases, until well away from the plate the layers have the free stream velocity v_0 . The layers between the free stream and the boundary are called *boundary layers* and are characterized by a velocity gradient dv/dy . From figure [8.1] we see that frictional shear stresses are present in these boundary layers.

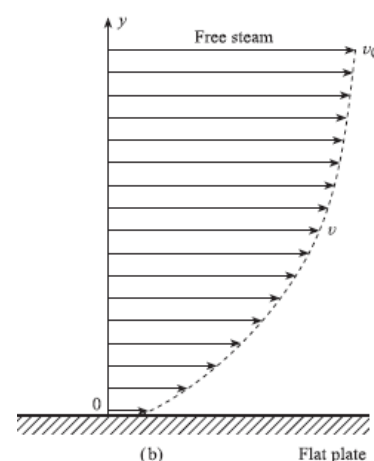
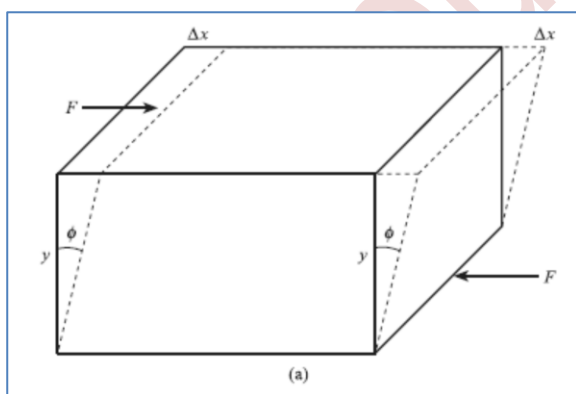


Figure 8.1 Shear stress and viscosity: (a) Deformation caused by shearing forces (b) Velocity distribution in boundary layers.

Liquids and gases:

Although liquids and gases have the common properties of fluids, they have distinctive properties of their own. A liquid is difficult to compress, i.e. there is a very small decrease in volume for a given increase in pressure, and it may be regarded as incompressible, i.e. density ρ is independent of pressure (but will depend on temperature). Gases are easy to compress, and density depends on both pressure and temperature.

For an ideal gas we have:

$$P = \rho \cdot R \cdot T \quad \text{Equation of state for ideal gas}$$

For real gases the above equation must be corrected by introducing an experimental compressibility factor or gas law deviation constant.

The amount of heat required to raise the temperature of a gas by a given amount depends on whether the gas is allowed to expand, i.e. to do work, during the heating process. A gas therefore has two specific heats: specific heat at constant volume C_V and specific heat at constant pressure C_P . If the expansion or contraction of a gas is carried out **adiabatically**, i.e.

Laminar and turbulent flow: Reynolds number

Experimental observations have shown that two distinct types of flow can exist.

The first is **laminar flow**, or viscous or streamline flow; this is shown for a circular pipe in Figure 8.2(a). Here the particles move in a highly ordered manner, retaining the same relative positions in successive cross-sections. Thus laminar flow in a circular pipe can be regarded as a number of annular layers: the velocity of these layers increases from zero at the pipe wall to a maximum at the pipe center with significant viscous shear stresses between each layer. Figure 12.2(a) shows the resulting velocity profile; this is a graph of layer velocity v versus distance r of layer from center, and is parabolic in shape.

The second type of flow, **turbulent flow**, is shown in Figure 8.2(b). This is highly disordered; each particle moves randomly in three dimensions and occupies different relative positions in successive cross-sections. As a result, the velocity and pressure at a given point in the pipe are both subject to small random fluctuations with time about their mean values. The viscous friction forces which cause the ordered motion in laminar flow are much smaller in turbulent flow. Figure 8.2(b) shows a typical velocity profile for turbulent flow in a circular pipe. It is obtained by taking a point r in the pipe and measuring the time average v of the velocity component, along the direction of flow at that point.

The **Reynolds number** tells us whether the flow in a given situation is laminar or turbulent. It is the dimensionless number:

$$Re = \rho \cdot U \cdot d / \mu$$

The Reynolds number represents the ratio of inertial forces (proportional to $\rho \cdot U \cdot d$) to viscous forces (proportional to η); thus a low value of Re implies laminar flow and a high value turbulent flow. The following is an approximate guide:

$Re < 2 \times 10^3$ – laminar flow

$2 \times 10^3 < Re < 10^4$ – transition region

$Re > 10^4$ – turbulent flow

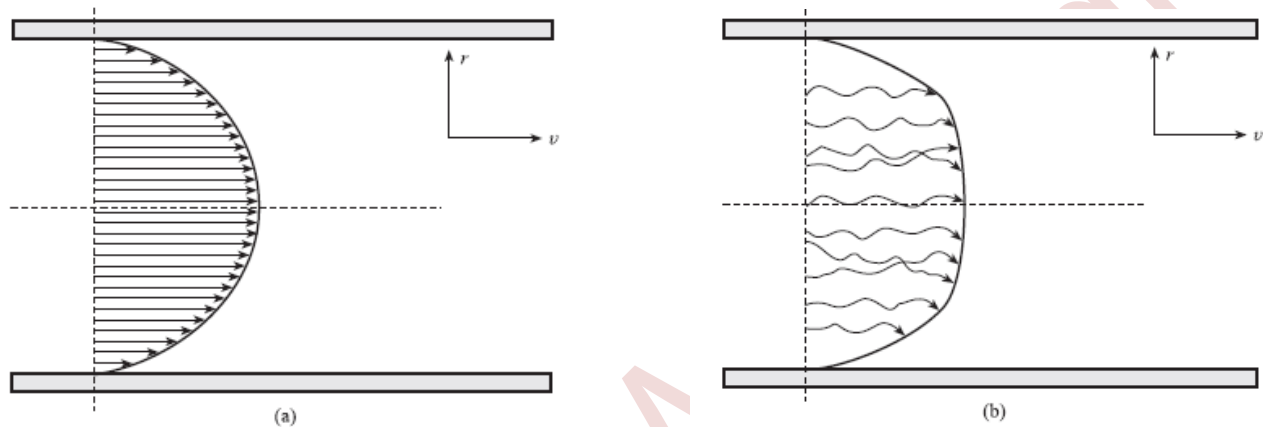


Figure 8.2 Types of flow and velocity profiles in a circular pipe: (a) Laminar (b) Turbulent

Continuity: conservation of mass and volume flow rate:

Figure 7.3 shows a stream tube through which there is a steady flow; since conditions are steady the principle of conservation of mass means that:

Mass of fluid entering in unit time = mass of fluid leaving in unit time

Conservation of mass flow rate: $\dot{m} = \rho \cdot U \cdot A$

Conservation of volume flow rate: $Q = U \cdot A$



Figure 8.3 Conservation of mass flow rate in a stream tube.

Total energy and conservation of energy

Potential energy given by: Potential energy = $m.g.z$

Kinetic energy given by: Kinetic energy = $\frac{1}{2} (mv^2)$

Flow work is often referred to as **pressure energy**; this is the energy possessed by a fluid when moving under pressure as part of a continuous stream. The *total energy* of a flowing fluid is the sum of pressure, kinetic and potential energies, so that:

$$\text{Fluid energy: Total energy/unit mass} = \frac{p}{\rho} + \frac{1}{2} \cdot v^{-2} + gz$$

Conservation of energy – incompressible fluid:

Measurement of velocity at a point in a fluid

This is important in investigational work, such as studies of the velocity distribution around an aerofoil in a wind tunnel, or measurement of the velocity profile in a pipe prior to the installation of a permanent flow meter. There are two main methods.

Pitot-static tube

An obstruction type primary element used mainly for fluid velocity measurement is the Pitot tube.

Principle

Consider Fig. 8.4 which shows flow around a solid body. When a solid body is held centrally and stationary in a pipeline with a fluid streaming down, due to the presence of the body, the fluid while approaching the object starts losing its velocity till directly in front of the body, where the velocity is zero. This point is known as the stagnation point. As the kinetic head is lost by the fluid, it gains a static head. By measuring the difference of pressure between that at normal flow line and that at the stagnation point, the velocity is found out. This principle is used in Pitot tube sensors.

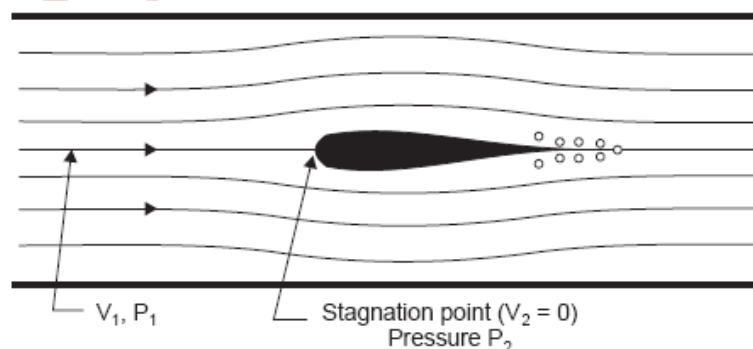


Figure 8.4 Flow around a solid body

The simplest Pitot tube consists of a tube with an impact opening of 3.125 mm to 6.35 mm diameter pointing towards the approaching fluid. This measures the stagnation pressure. An ordinary upstream tap can be used for measuring the line pressure.

A common industrial type of Pitot tube consists of a cylindrical probe inserted into the air stream, as shown in Fig. 8.4. Fluid flow velocity at the upstream face of the probe is reduced substantially to zero. Velocity head is converted to impact pressure, which is sensed through a small hole in the upstream face of the probe. A corresponding small hole in the side of the probe senses static pressure. A pressure instrument measures the differential pressure, which is proportional to the square of the stream velocity in the vicinity of the impact pressure sensing hole. The velocity equation for the Pitot tube is given by:

$$v = C_{pitot} \cdot \sqrt{2gh}$$

Where C_{pitot} is the Pitot tube constant.

Figure 8.5 shows a typical Pitot tube which also shows the taps for sensing static pressure. The total pressure developed at the point where the flow is stagnated is assumed to occur at the tip of a Pitot tube or at a specific point on a bluff body immersed in the stream.

The Pitot tube causes practically no pressure loss in the flow stream. It is normally installed through a nipple in the side of the pipe. It is frequently installed through an isolation valve, so that it can be moved back and forth across the stream to establish the profile of flow velocity.

Certain characteristics of Pitot tube flow measurement have limited its industrial application. For true measurement of flow, it is essential to establish an average value of flow velocity. To obtain this with a Pitot tube, it is necessary to move the tube back and forth across the stream to establish the velocity at all points and then to take an average. For high-velocity flow streams, it is required to provide necessary stiffness and strength.

A tube inserted in a high-velocity stream has a tendency to vibrate and get broken. As a result, Pitot tubes are generally used only in low-to-medium flow gas applications where high accuracy is not required.

Figure 8.5 Typical Pitot tube

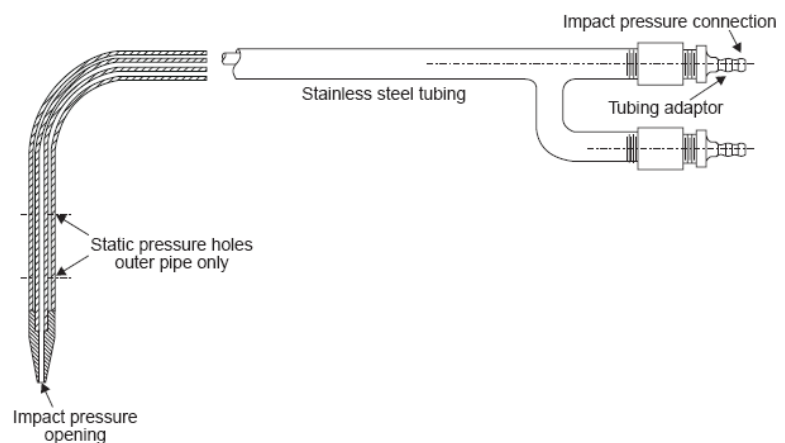


Figure 8.6 shows the Pitot - static tube. At the impact hole part of the fluid is brought to rest; this part has therefore no kinetic energy, only pressure energy. At the static holes the fluid is moving and therefore has both kinetic and pressure energy. This creates a pressure difference $P_I - P_S$ which depends on velocity v .

Applying the incompressible equation to air at standard temperature ($20\text{ }^{\circ}\text{C}$) and pressure ($P_S = 10^5\text{ Pa}$), with $\rho = 1.2\text{ kg m}^{-3}$, gives $\Delta P = 0.6v^2$. Thus at $v = 5\text{ m s}^{-1}$ we have $\Delta P = 15\text{ Pa}$, $\Delta P/P_S = 1.5 \times 10^{-4}$; and at $v = 100\text{ m s}^{-1}$, $\Delta P = 6 \times 10^3\text{ Pa}$, $\Delta P/P_S = 6 \times 10^{-2}$. The small $\Delta P/P_S$ ratio means that for $v < 100\text{ m s}^{-1}$, the difference in density between the air at the impact and static holes is negligible; the error introduced by using the incompressible equation is within 1%.

The above very low differential pressures mean that special pressure transmitters must be used. One such transmitter uses a linear variable differential transformer to sense the deformation of a diaphragm capsule with a large area; this gives a 4 to 20 mA current output proportional to input differential pressure in the range 0 to 250 Pa. Figure 7.6 shows a computer-based measurement system incorporating this transmitter for measuring air velocities in the range 0 to 20 m s^{-1} . The amplifier converts the transmitter output to a voltage signal between 0.51 and 2.55 V. The analogue-to-digital converter gives an 8-bit parallel digital output signal corresponding to decimal numbers D between 51 and 255.

The above system is only suitable for measuring the time average of the velocity at a point in a fluid. The system frequency response is insufficient for it to measure the rapid random velocity fluctuations present in turbulent flow.

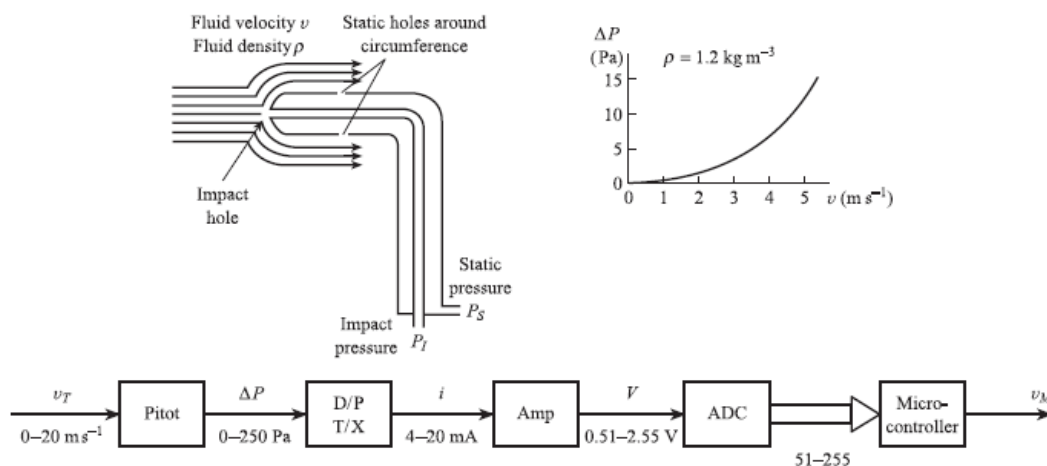


Figure 8.6 Pitot-static tube.

Hot Wire probes

INTRODUCTION

The hot-wire anemometer has been used extensively for many years as a research tool in fluid mechanics. hot-wire anemometry will refer to the use of a small, electrically heated element exposed to a fluid medium for the purpose of measuring a property of that medium. Normally, the property being measured is the velocity. Since these elements are sensitive to heat transfer between the element and its environment, temperature and composition changes can also be sensed.

Figure 8.7 shows a hot-wire anemometer probe. Typical dimensions of the wire sensor are 0.00015 to 0.0002 inches (0.0038 to 0.005 mm) in diameter and 0.040 to 0.080 inches (1.0 to 2.0 mm) long. This is the type of hot wire that has been used for such measurements as turbulence levels in wind tunnels, flow patterns around models and blade wakes in radial compressors. The film type of sensor is shown in Figure 7.8. The hot film is used in regions where a hot wire probe would quickly break such as in water flow measurements.

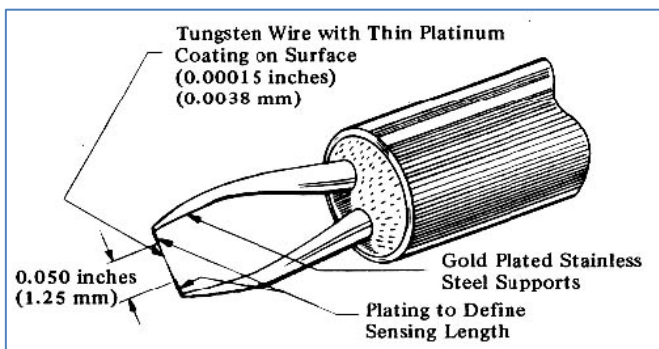


Figure 8.7 hot wire

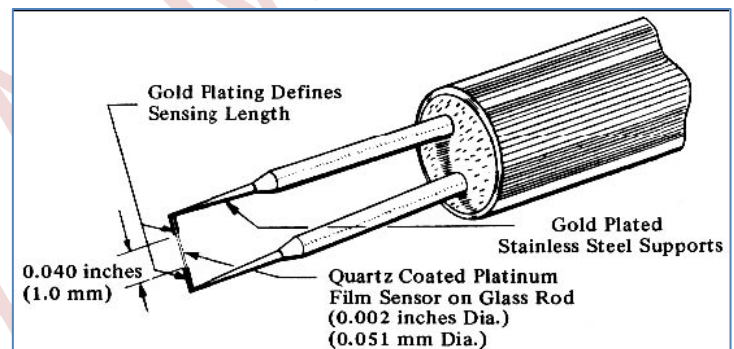


Figure 8.8 hot film hot wire

Modes of anemometer operation:

- **Constant Current (CCA)**
- **Constant Temperature (CTA)**

Hot wire can be using as a **Constant Temperature Anemometer (CTA)**. It works based on the fact that the probe's resistance will be proportional to the temperature of the hot wire. The bridge circuit shown in Figure 8.9 below is set up by setting the adjustable resistor to the resistance you wish the probe and its leads to have during operation. (The other two legs of the bridge have identical resistance.) The servo amplifier tries to keep the error voltage zero (meaning the resistances of the two lower legs of the bridge match). It will adjust the bridge voltage such that the current through the probe heats it to the temperature which gives the selected resistance. When we put the probe in a flow, the air (or water) flowing over it will try to cool it. In order to maintain the temperature (resistance) constant, the bridge voltage will have to be increased. A very fine hot

wire by itself cannot respond to changes in fluid velocity at frequencies above about 500 Hz. By compensating for frequency lag with a non-linear amplifier this response can be increased to values of 300 to 500 kHz.

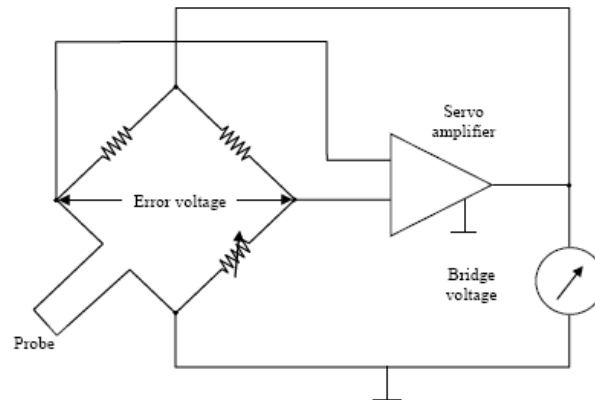


Figure 8.9 Constant Temperature Anemometer (CTA)

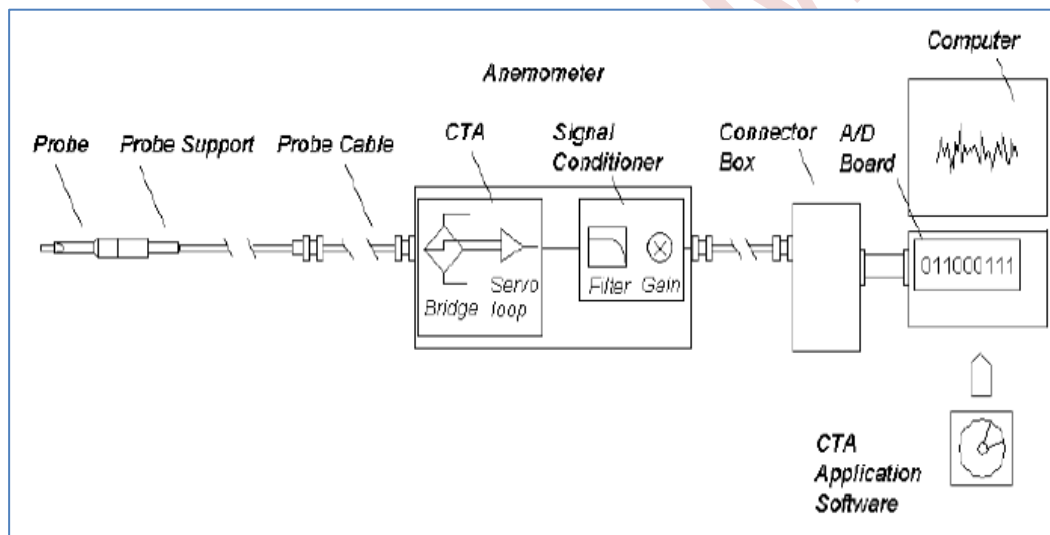


Figure 8.10 Basic CTA Measuring Chain

Features

- Measures velocities from a few cm/s to supersonic.
- High temporal resolution: fluctuations up to several hundred kHz.
- High spatial resolution: eddies down to 1 mm or less.
- Measures all three velocity components simultaneously.
- Provides instantaneous velocity information.

Principles of operation:

Consider a thin wire mounted to supports and exposed to a velocity U . When a current is passed through wire, heat is generated ($I^2 R_w$). In equilibrium, this must be balanced by heat loss (primarily convective) to the surroundings.

If velocity changes, convective heat transfer coefficient will change, wire temperature will change and eventually reach a new equilibrium.

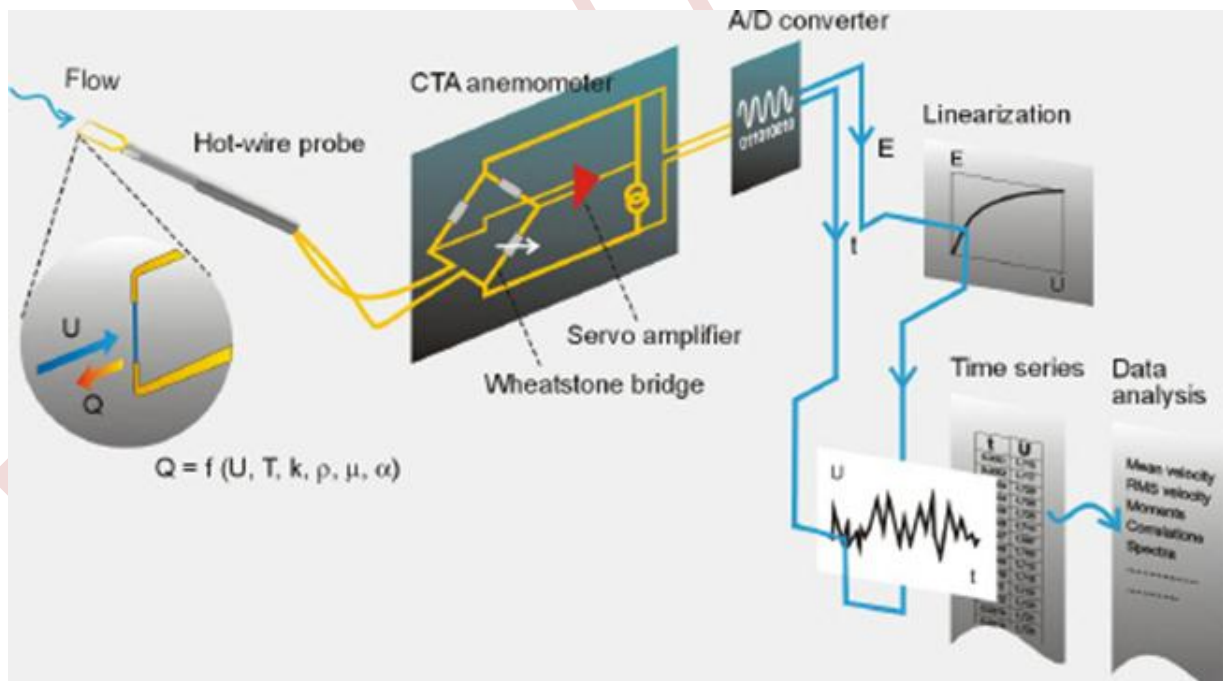
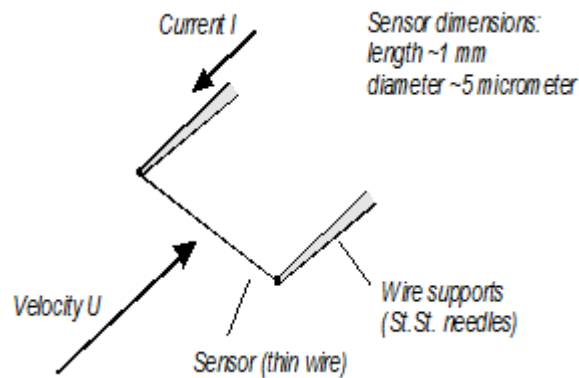


Figure 8.11

PROBE TYPES

Hot-Wire Sensors

A hot-wires type sensor must have two characteristics to make it a useful device:

- A high temperature coefficient of resistance
- An electrical resistance such that it can be easily heated with an electrical current at practical voltage and current levels.

The most common wire materials are tungsten, platinum and a platinum-iridium alloy. Tungsten wires are strong and have a high temperature coefficient of resistance, ($0.004/^{\circ}\text{C}$). However, they cannot be used at high temperatures in many gases *because of poor oxidation resistance*. Platinum has good oxidation resistance, has a good temperature coefficient ($0.003/^{\circ}\text{C}$), but is very weak, particularly at high temperatures. The platinum-iridium wire is a compromise between tungsten and platinum with good oxidation resistance, and more strength than platinum, but it has a low temperature coefficient of resistance ($0.00085/^{\circ}\text{C}$). Tungsten is presently the more popular hot wire material. A thin platinum coating is usually applied to improve bond with the plated ends and the support needles.

Hot-Film Sensors

The hot-film sensor is essentially a conducting film on a ceramic substrate. The sensor shown in Figure 7.8 is a quartz rod with a platinum film on the surface. **Gold plating on the ends** of the rod isolates the sensitive area and provides a heavy metal contact for fastening the sensor to the supports. When compared with hot wires the cylindrical hot-film sensor has the following advantages:

- Better frequency response (when electronically controlled) than a hot wire of the same diameter because the sensitive part of the sensor is distributed on the surface rather than including the entire cross section as with a wire. Although hot wires are typically much smaller in diameter.
- Lower heat conduction to the supports (end loss) for a given length to diameter ratio due to the low thermal conductivity of the substrate material. A shorter sensing length can thus be used.
- More flexibility in sensor configuration. Wedge, conical, parabolic and flat surface shapes are available.
- Less susceptible to fouling and easier to clean. A thin quartz coating on the surface resists accumulation of foreign material. Fouling tends to be a direct function of size.

The metal film thickness on a typical film sensor is less than 1000 Angstrom units, causing the physical strength and the effective thermal conductivity to be determined almost entirely by the substrate material. Most films are made of platinum due to its good oxidation resistance and the resulting long-term stability. The ruggedness and stability of film sensors have led to their use for many measurements that have previously been very difficult with the more fragile and less stable hot wires.

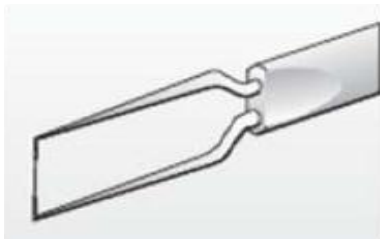
Due to the fact that **hot film probes are typically of a much larger diameter than wires**, they will not respond as quickly as a typical wire and therefore will not measure turbulent fluctuations at as high a frequency as hot wires.

Advantages:

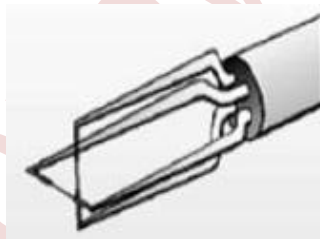
- Good Frequency response: Measurements to several hundred kHz possible, 1 MHz also feasible.
- Velocity Measurement: measures magnitude and direction of velocity and velocity fluctuations, Wide velocity range
- Temperature Measurements
- Two Phase Flow: Measurements in flows containing continuous turbulent phase and distributed bubbles.
- Signal to noise ratio: have low noise levels. Resolution of 1 part in 10000 is accomplished.
- Signal Analysis: Output is continuous analogue signal, both time domain and frequency domain analysis can be carried out. Output can also be processed by digital systems.
- Measurement of turbulent quantities like vorticity, dissipation rate etc.

Classification of Hot Wire Probes

On the basis of number of sensors:



Single Sensor Probe



Dual Sensor Probe



Triple Sensor Probe

Problem Sources:

- Bubbles in Liquids: Effect of bubbling on portion of typical calibration curve
- Eddy shedding: from cylindrical sensors occurs at $Re \sim 50$. Vibrations from prongs and probe supports causes vibrate due to eddy shedding from them or due induced vibrations.
- Temperature Variations.

Anemometer

These anemometers have been used to measure air and gas flows in a variety of applications.

They are also used to measure the velocity of wet and dry gases.

Designs of Mechanical Anemometers:

1. Vane anemometer
2. three-cup anemometer
3. Impeller anemometer.

Vane Anemometer

Fig. 8.12 shows the vane-design. In this type, the vanes rotate in response to airflow with the angular velocity of the vanes being proportional to the wind speed. When a portable unit is required or when the local readout is satisfactory, vane motion is passed to the indicator through a gear and spring assembly. If the reading is to be remote, a magnetically coupled or capacitive coupled pickup can be used to generate a transmission signal.

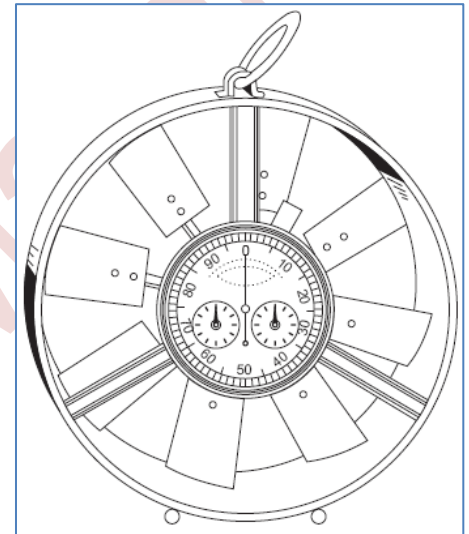


Figure 8.12

Three-Cup Anemometer

Fig. 8.13 shows a three-cup anemometer. This type of anemometer is not sensitive to the direction of the fluid. In this design the shaft drives a direct current tachometer generator with an output voltage that is proportional to the wind speed. This signal may be used to drive a remote mounted indicator recorder.

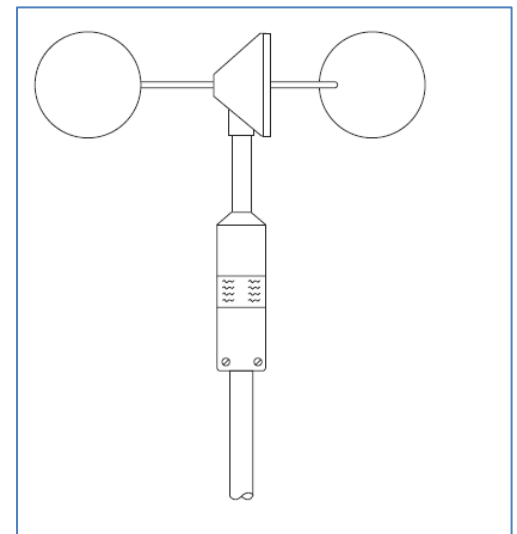


Figure 8.13

Impeller Anemometer

The impeller design is shown in Fig. 8.14. This anemometer also has a shaft-driven tachometer. Since the tail on the impeller design always keep the impellers pointed into the wind, this instrument can be used to detect both wind speed and wind direction. The speed of response for anemometer is given in meters of wind and is known as distance constant.

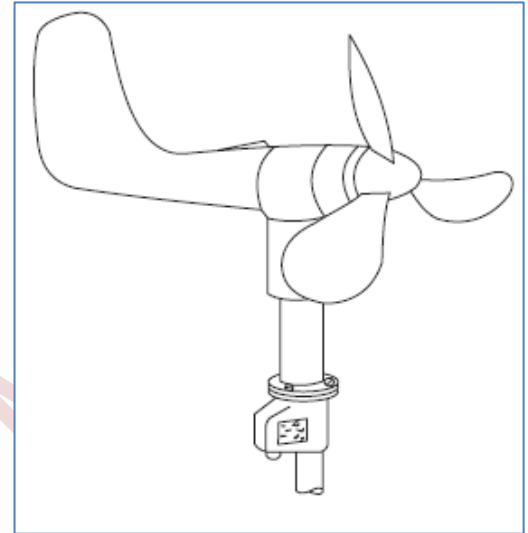


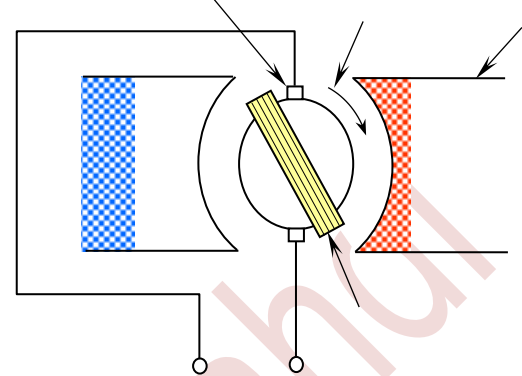
Figure 8.14

Angular velocity:

Definition: Angular Velocity is turn/time (r.p.m):

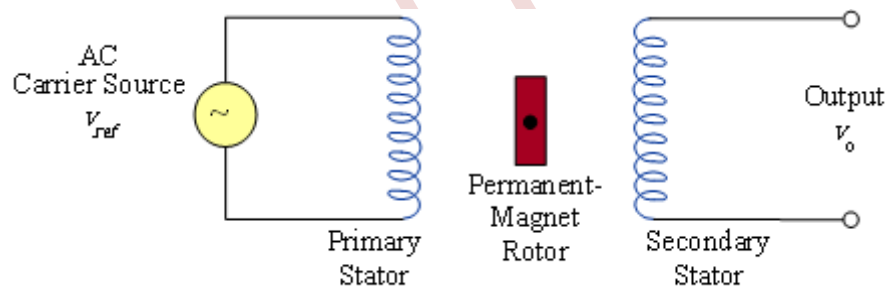
$$\omega = \frac{\theta}{t}$$

DC Tachometer (Angular Velocity):



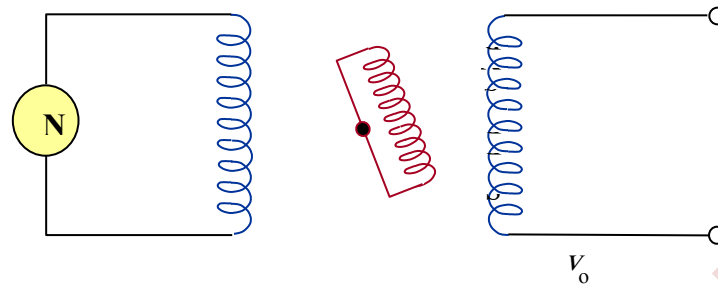
- The rotor is directly connected to the rotating object.
- The output signal that is induced at the rotating coil is picked up using a commutator device (consists of low resistance carbon brushes)
- Commutator is stationary but makes contact with the split slip rings
- Generated voltage is (Faraday's Law)

Permanent Magnet AC Tachometer:



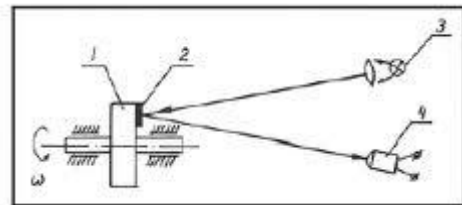
- When the rotor is stationary or moving in a quasi-static manner the output voltage will be constant.
- As the rotor moves, an additional voltage, proportional to the speed of the rotor will be induced.
- The output is an amplitude modulated signal proportional to the rotor speed and demodulation is necessary.
- Direction is obtained from the phase angle.
- Main advantage of AC tachometers is that they have no slip rings or brushes.
- For low frequency applications (~5Hz), supply with 60Hz is adequate.
- Sensitivity is in the range 50 – 100mV/rad/s.

AC Induction Tachometer:



- Similar in construction to an induction motor. Rotor windings are shorted.
- The induced voltage in the rotor windings is a modulated signal of the supply. Modulation is due to the speed of the rotor.
- The output voltage on the secondary is a result of primary and rotor windings and is supply modulated by the speed.
- Main advantage of AC tachometers is that they have no slip rings or brushes

Photoelectric Tachometer:



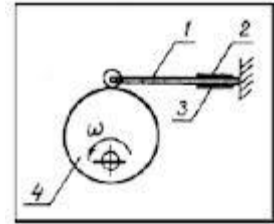
Structure: A disk with reflecting markings attached to the shaft.

A light source and a light detector.

Output: a train of pulses whose frequency is proportional to shaft's RPM.

Strain Gauge Tachometer:

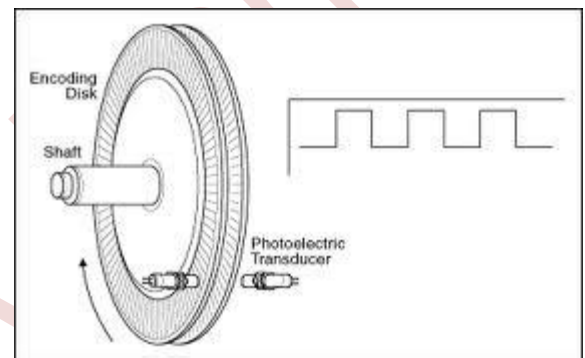
Structure: A thin rod with a bonded strain gauge attached. The end of the rod has a small wheel that rests on the disk attached to the shaft.



Output: A sinusoidal waveform whose frequency is proportional to the RPM.

Optical Sensor:

Structure: A light emitter and a light detector.





MEASUREMENT OF FLOW

Introduction:

The material which is in a liquid or gaseous state, flow can be quantified as either the **mass flow rate** or the **volume flow rate**, with the latter being the volume of material that flows in one unit of time. Of the two, a flow measurement in terms of 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.

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, as different techniques are appropriate for each.

Conveyor-Based Methods:

Conveyor-based methods are appropriate for measuring the flow of solids in the form of powders or small granular particles. Such powders and particles are produced commonly 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.

Coriolis Flow meter

As well as sometimes being known by the alternative name of inertial flow meter, the Coriolis flow meter is often referred to simply as a mass flow meter because of its dominance in the mass flow meter market. Coriolis meters are used primarily to measure the mass flow rate of liquids, although they have also been used successfully in some gas-flow measurement applications. The flow meter consists either of a pair of parallel vibrating tubes or as a single vibrating 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 9.1a, and a U-shaped tube is shown in more detail in Figure 9.1b. 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. Vibrations in the two tubes, or the two parallel sections of a single tube, are 180 degrees out of phase.

The vibratory motion of each tube causes forces on the particles in the flowing fluid. These forces induce motion of the fluid particles in a direction that is orthogonal to the direction of flow, which produces a Coriolis force. This Coriolis force causes a deflection of the tubes that is superimposed on top of the vibratory motion. 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 flow meter causes it to suffer a significant pressure drop, although this is much less evident in straight tube designs.

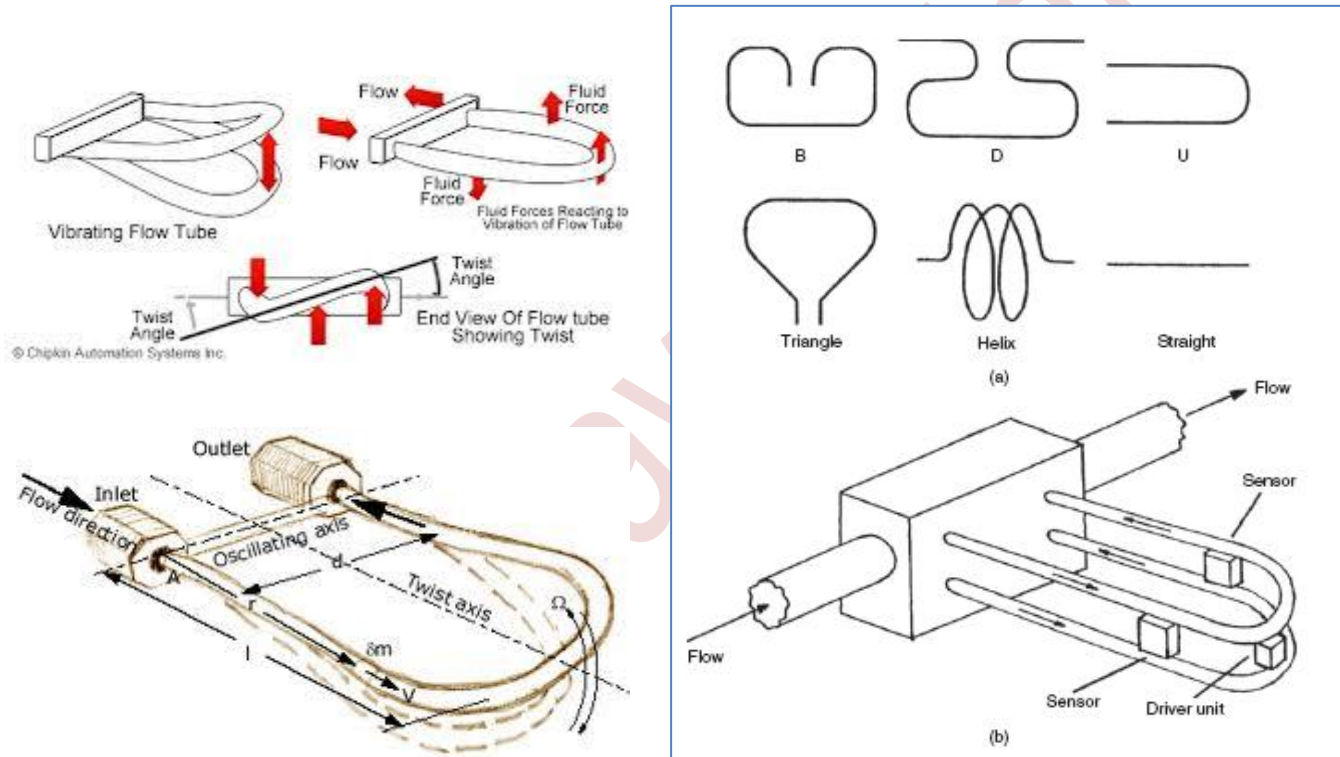
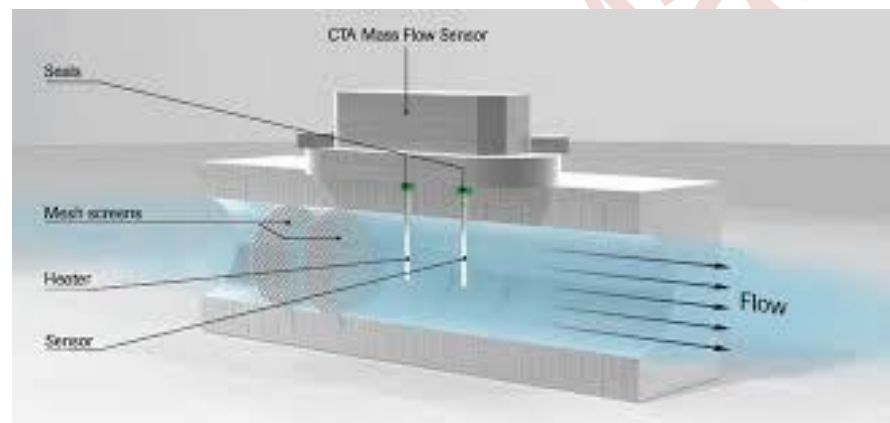


Figure 9.1

Thermal Mass Flow Measurement

Thermal mass flow meters are used primarily to measure the flow rate of gases. The principle of operation is to direct the flowing material past a heated element. The mass flow rate is inferred in one of two ways: (a) by measuring the temperature rise in the flowing material or (b) by measuring the heater power required to achieve a constant set temperature in the flowing material. In both cases, the specific heat and density of the flowing fluid must be known. Typical measurement uncertainty is $\pm 2\%$. Standard instruments require the measured gas to be clean and noncorrosive. However, versions made from special alloys can cope with more aggressive gases. Tiny versions of thermal mass flow meters have been developed that can measure very small flow rates in the range of nano liters (10⁻⁹ liters) or microliters (10⁻⁶ liters) per minute.



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 later. 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 flow meter.

Variable Area Flow meters (Rotameters)

In the variable area flow meter (which is also sometimes known as a rotameter), the differential pressure 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, inexpensive, and used extensively throughout industry, accounting for about 20% of all flow meters sold. Normally, because this type of instrument only gives a visual indication of flow rate, it is of no use in automatic control schemes. However, special versions of variable area flow meters 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.

In its simplest form, shown in Figure 9.2, the instrument consists of a tapered glass tube containing a float that takes up a stable position where its submerged weight is balanced by the up thrust 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 least expensive instruments is typically $\pm 5\%$, but more expensive versions offer measurement inaccuracies as low as $\pm 0.5\%$.

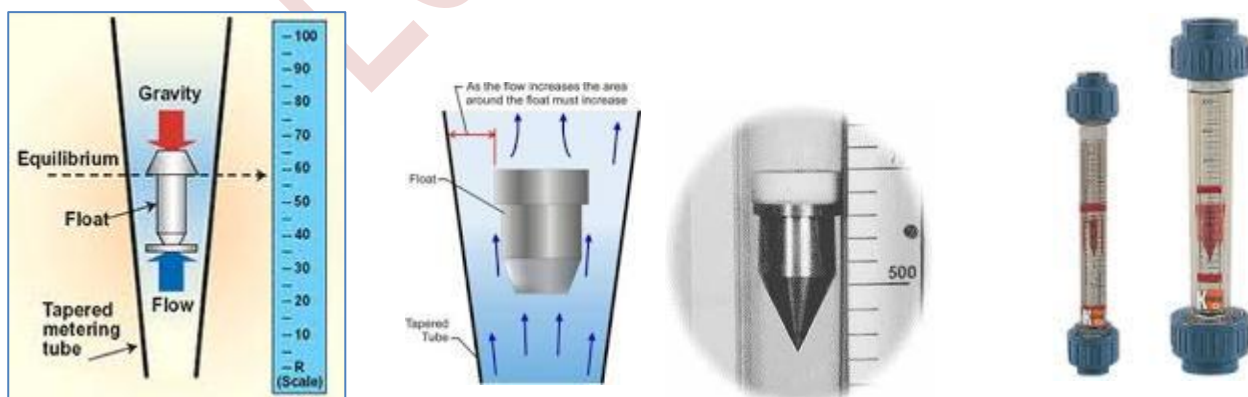


Figure 9.2

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, Venturi tube, flow nozzle, and Dall flow tube, as illustrated in Figure 9.3. 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 that can arise when the pressure difference is small. Therefore, the normal procedure is to use a differential pressure transducer, which is commonly a diaphragm-type device.

The Pitot static tube is another 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 an nubar is a type of multiport Pitot tube that measures 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; 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 process industries is to specify a length of 10 times 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 depend 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 9.3

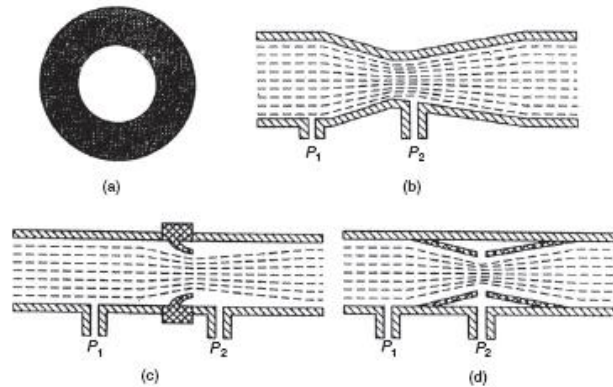
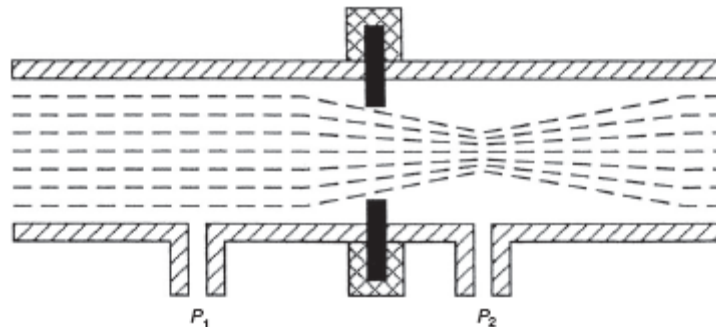


Figure 9.4 illustrates approximately the way in which the flow pattern is interrupted when an orifice plate is inserted into a pipe. Other obstruction devices also have a similar effect to this, although the magnitude of pressure loss is smaller. Of particular interest is the fact that the minimum cross-sectional area of flow occurs not within the obstruction but at a point downstream of there.

Figure 9.4



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, inexpensive, 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 $\pm 2\%$ and may approach $\pm 5\%$. 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, thereby reducing its diameter gradually 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 buildup 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.

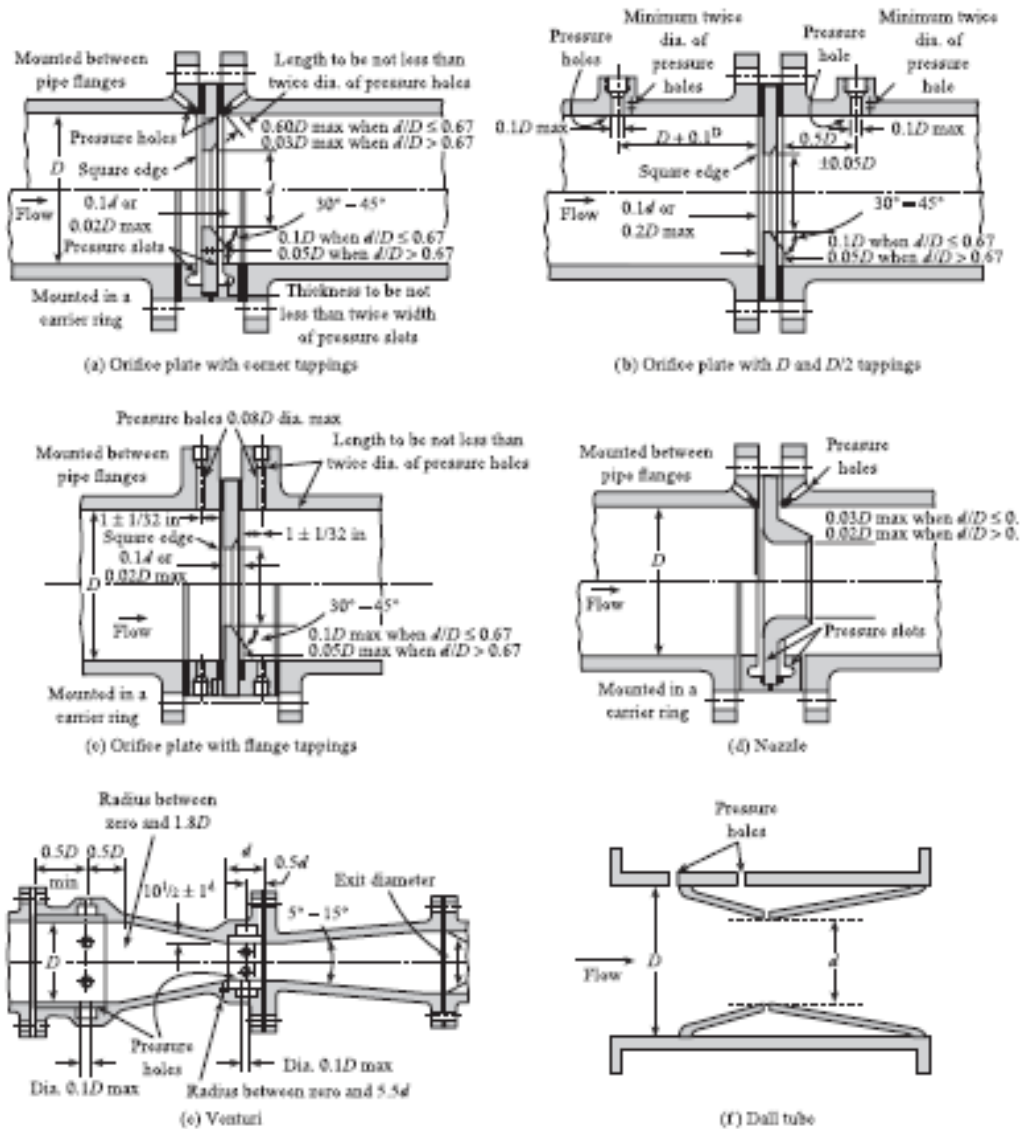
Venturis and similar devices

A number of obstruction devices are available that are specially designed to minimize 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 $\pm 1\%$. However, the complex machining required manufacturing 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 a 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, which gives the Dall flow tube an advantage in cost over the Venturi, although the typical measurement inaccuracy is a little higher ($\pm 1.5\%$). 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: This nozzle is of simpler construction still and is therefore less expensive 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.



Differential pressure flow meter according to British standard Institution.

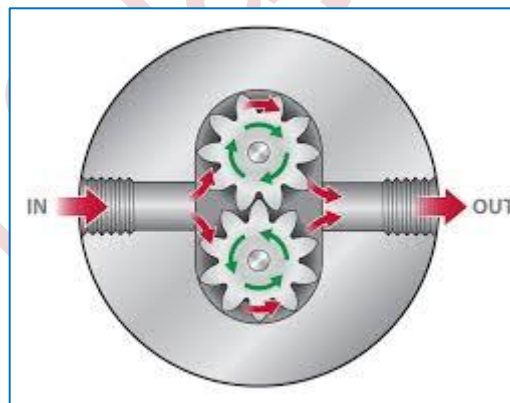
Pitot static tube

The Pitot static tube is used mainly 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 flow meters. 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 non-uniform flow. Multiple Pitot tubes are normally used to do this.

Positive Displacement Flow meters

Positive displacement flow meters account for nearly 10% of the total number of flow meters used in industry and are used in large numbers for metering domestic gas and water consumption. The least expensive instruments have a typical inaccuracy of about $\pm 2\%$, but the inaccuracy in more expensive ones can be as low as $\pm 0.5\%$. 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 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 meters 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.



Turbine Meters

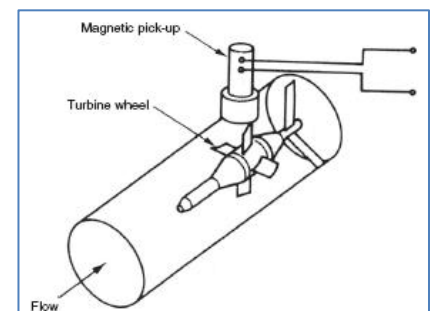
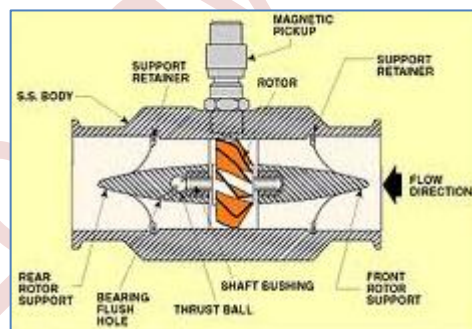
A turbine flow meter consists of a multi-bladed wheel mounted in a pipe along an axis parallel to the direction of fluid flow in the pipe, as shown in Figure 9.5. The flow of fluid past the wheel causes it to rotate at a rate proportional to the volume flow rate of the fluid. This rate of rotation has traditionally been measured by constructing the flow meter 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.

Provided that the turbine wheel is mounted in low-friction bearings, measurement inaccuracy can be as low as $\pm 0.2\%$. However, turbine flow meters are less rugged and reliable than flow restriction-type instruments and are affected badly by any particulate matter in the flowing fluid. Bearing wear is a particular problem, which also imposes 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.

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.

Figure 9.5

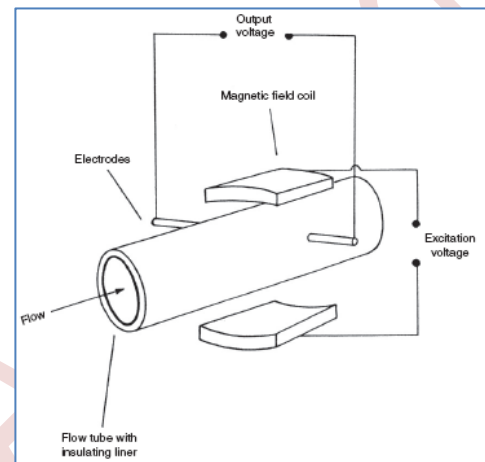
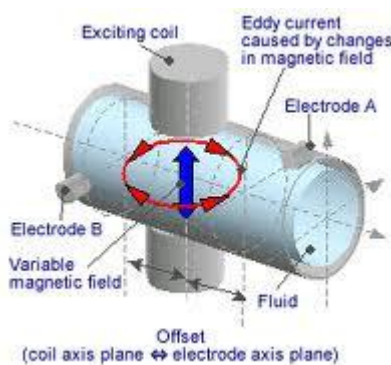


Electromagnetic Flow meters:

Electromagnetic flow meters, sometimes known just as magnetic flow meters, are limited to measuring the volume flow rate of electrically conductive fluids. A typical measurement inaccuracy of around $\pm 1\%$ is acceptable in many applications, but the instrument is expensive both in terms of the initial purchase cost and in running costs, mainly due to its electricity consumption. A further reason for its 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 9.6, 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 that is unaffected by most types of flowing fluids, such as stainless steel, platinum–iridium alloys, Hastelloy, titanium, and tantalum. In the case of rare metals in this list, the electrodes account for a significant part of the total instrument cost.

Figure 9.6



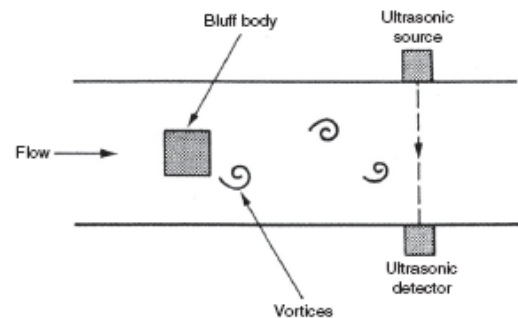
Vortex-Shedding Flow meters

The vortex-shedding flow meter 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 un stream lined obstacle (known as a bluff body) in a fluid-carrying pipe, as indicated in Figure 9.7. When fluid flows past the obstacle, boundary layers of viscous, slow-moving fluid are formed along 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 low 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 $\pm 1\%$ of full-scale reading, although 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 that have a better immunity to such vibrations.

Figure 9.7



Ultrasonic Flow meters

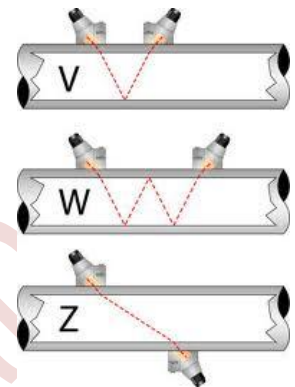
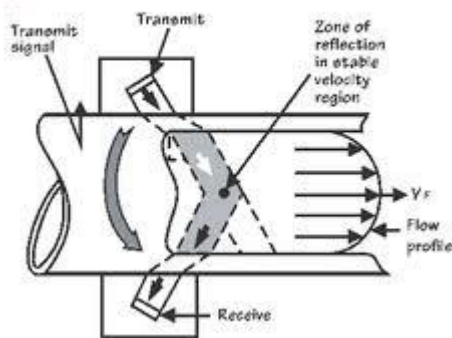
The ultrasonic technique of volume flow rate measurement is, like the magnetic flow meter as show in figure 9.8, a noninvasive method. It is not restricted to conductive fluids, however, and is particularly useful for measuring the flow of corrosive fluids and slurries. In addition to its high reliability and low maintenance requirements, a further advantage of an ultrasonic flow meter over an electromagnetic flow meter is that the instrument can be clamped externally onto existing pipework instead of being inserted as an integral part of the flow line. As the procedure of breaking into a pipeline to insert a flow meter can be as expensive as the cost of the flow meter itself, the ultrasonic flow meter has enormous cost advantages. Its clamp-on mode of operation also has significant safety advantages in avoiding the possibility of personnel installing flow meters 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 flow meters, although usage continues to expand year by year.

Two different types of ultrasonic flow meter exist that employ distinct technologies—one based on Doppler shift and the other on trans it 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 is not. To reject both, having only tried out one, is therefore a serious mistake. Ultrasonic flow meters have become available that combine both Doppler shift and transit time technologies. Particular care has to be taken to ensure a stable flow profile in ultrasonic flow meter 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 flow meter application has shown failure to meet this stable flow profile requirement to be a significant factor. figure 8.8

Doppler ultrasonic



Choice between Flow meters for Particular Applications

The number of relevant factors to be considered when specifying a flow meter for a particular application is very large. 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, range ability, 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, economic viability must be assessed, which must take into account not only the purchase cost, but also reliability, installation difficulties, maintenance requirements, and service life.

Where only a visual indication of 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 instruments currently in use in industry. Other forms of differential pressure meters and electromagnetic flow meters 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.

Calibration of Flow meters

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 $\pm 0.1\%$) are necessary and the expensive procedures necessary to achieve these levels 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 $\pm 5\%$ is acceptable) and relatively inexpensive calibration procedures are sufficient.

The accuracy of flow measurement is affected greatly 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 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 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 to 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.

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-measuring and velocity-measuring instruments are involved. In the case of Coriolis and thermal mass flow meters, 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 normally provided by the instrument manufacturer.

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

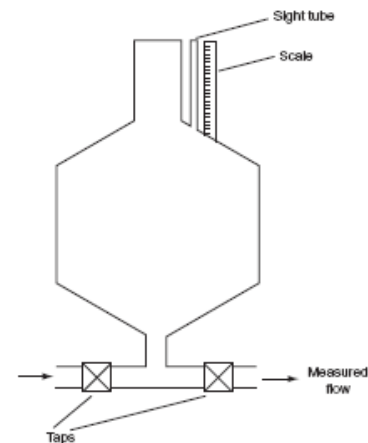
Calibrated tank

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 9.9, 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, which 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 affected by flow acceleration and deceleration characteristics. This therefore excludes instruments such as differential pressure meters (orifice plate, flow nozzle, Venturi, Dall flow tube, Pitot tube), turbine flow meters, and vortex-shedding flow meters.

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.

Figure 9.9



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 flow meters. 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.