# 1 Flow

## 1.1 Introduction

Industrial flow measurements include measuring of flow rate of solids, liquids and gases. There are two basic ways of measuring flow ; one on volumetric basis and the other on weight basis. Solid materials are measured in terms of either weight per unit time or mass per unit time. Very rarely solid quantity is measured in terms of volume. Liquids are measured either in volume rate or in weight rate. Gases are normally measured in volume rate. In this chapter, the flow measurements of liquids and gases will be discussed in detail rather than that of solids.

Fluids are classified into two types, namely incompressible and compressible. Fluids in liquid phase are incompressible whereas fluids in gaseous phase are compressible. Liquid occupies the same volume at different pressures where as gases occupy different volumes at different pressures. This point has to be taken care of while calibrating the flow meters. The measurements taken at actual conditions should be converted either to Standard temperature (0°C) and pressure (760 mm Hg) base (STP base) or to Normal temperature (20°C) and pressure (760 mm Hg) base (NTP base).

## 1.2 Units of Flow

The units used to describe the flow measured can be of several types depending on how the specific process needs the information.

**Solids.** Normally expressed in weight rate like Tonnes/hour, Kg/minute etc.

**Liquids.** Expressed both in weight rate and in volume rate.

**Examples :** Tonnes/hour, Kg/minute, litres/hour, litres/minute, $m^3$/hour etc.

**Gases.** Expressed in volume rate at NTP or STP like Std $m^3$/hour, $Nm^3$/hour etc.

**Steam.** Expressed in weight rate like Tonnes/hour, Kg/minutes etc. Steam density at different temperatures and pressures vary. Hence the measurement is converted into weight rate of water which is used to produce steam at the point of measurement.

## 1.3 Measurement of Flow

Flow meter is a device that measures the rate of flow or quantity of a moving fluid in an open or closed conduit. Flow measuring devices are generally classified into four groups.

They are :

**1. Mechanical type flow meters.** Fixed restriction variable head type flow meters using different sensors like orifice plate, venturi tube, flow nozzle, pitot tube, dall tube, quantity meters like positive displacement meters, mass flow meters etc. fall under mechanical type flow meters.

**2. Inferential type flow meters.** Variable area flow meters (Rotameters), turbine flow meter, target flow meters etc.

**3. Electrical type flow meters.** Electromagnetic flow meter, Ultrasonic flow meter, Laser doppler Anemometers etc. fall under electrical type flow meters.

**4. Other flow meters.** Purge flow regulators, Flow meters for Solids flow measurement, Cross-correlation flow meter, Vortex shedding flow meters, flow switches etc.

The working principle construction, calibration etc. of the above flow meters will be discussed in the following sections.

## 1.4 Mechanical Flowmeters

Fixed restriction variable head type flow meters using different sensors like orifice plate, venturi tube, flow nozzle, pitot tube, dall tube, quantity meters like positive displacement meters, mass flow meters are the popular types of mechanical flow meters.

### 1.4.1 Theory of Fixed Restriction Variable Head Type Flowmeters

In the variable head type flow meters, a restriction of known dimensions is generally introduced into pipeline, consequently there occurs a head loss or pressure drop at the restriction with increase in the flow velocity. Measurement of this pressure drop is an indication of the flow rate.

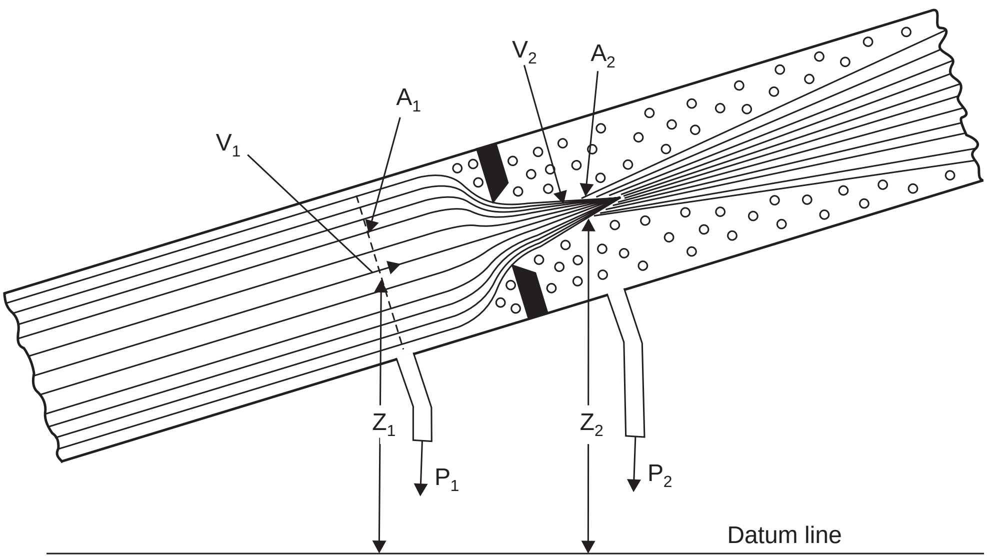



**Fig. 1.1** Schematic representation of a one dimensional flow system with a restriction

Head—type flow measurement derives from Bernoulli's theorem which states that in a flowing stream, the sum of the pressure head, the velocity head and the elevation head at one point is equal to their sum at another point in the direction of flow plus the loss due to friction between the two points. Velocity head is defined as the vertical distance through which a liquid would fall to attain a given velocity. Pressure head is the vertical distance which a column of the flowing liquid would rise in an open-ended tube as a result of the static pressure.

In general, a one—dimensional flow system is assumed. The schematic representation of such a system with a restriction in the pipeline is shown in Fig. 1.1.

**1.4.1.1 Flow of Incompressible Fluids in Pipes**

Section-1 is the position of upstream tap and Section-2 that for downstream. The terms T, A, ρ, V, P and Z represent Temperature, Area, Density, Stream velocity, Pressure and Central line elevation respectively. If this elevation is quite small such that $Z_2 - Z_1$ is negligible, the Bernoulli's equation for an incompressible ($\rho_1 = \rho_2$) frictionless and adaptive flow is written as

$$\frac{P_1}{\rho} + \frac{V_1^2}{2g} = \frac{P_2}{\rho} + \frac{V_2^2}{2g} \qquad ...(1.1)$$

where $g$ = acceleration due to gravity, giving

$$P_1 - P_2 = \frac{V_2^2 \rho}{2g} [1 - (V_1/V_2)^2] \qquad ...(1.2)$$

The continuity equation for this type of flow is

$$Q = A_2V_2 = A_1V_1 \qquad ...(1.3)$$

where Q = volume flow rate in $m^3$/sec.

Combining equations (1.2) and (1.3) and manipulating, one gets

$$Q = A_2V_2 = \frac{A_2}{\sqrt{[1-(A_2/A_1)^2]}} \left[\sqrt{\frac{2g(P_1 - P_2)}{\rho}}\right] = A_2M_{va} \sqrt{2gh} \qquad ...(1.4)$$

where $M_{va} = \dfrac{1}{\sqrt{1-\left(\dfrac{A_2}{A_1}\right)^2}}$ = Velocity approach factor

$h = \dfrac{P_1 - P_2}{\rho}$ = Differential head.

This is equation for the ideal volume flow rate.

For actual flow conditions with frictional losses present, a correction to this formula is necessary. Besides, the minimum area of flow channel occurs not at the restriction but at some point slightly downstream, known as the 'Venacontracta'. This in turn depends on the flow rate. While the tapping positions are fixed, the position of maximum velocity changes with changing flow rate.

The basic equations are :

$$V = K_1 \sqrt{h} \qquad ...(1.5)$$

$$Q = K_1A \sqrt{h} \qquad ...(1.6)$$

$$W = K_1A \sqrt{h}\, P \qquad ...(1.7)$$

where V = Velocity of Fluid

Q = Volume flow rate

W = Mass flow rate.

A = Cross-sectional area of the pipe.

$h$ = differential head between points of measurement.

$\rho$ = density of the flowing fluid

$K_1$ = Constant which includes ratio of cross-sectional area of pipe to cross-sectional area of nozzle or other restrictions.

#### 1.4.1.2 β Ratio

Most variable head meters depend on a restriction in the flow path to produce a change in velocity. For the usual circular pipe, the Beta ratio is the ratio between the diameter of the restriction and the inside diameter of the pipe.

$$\beta = d/D \quad ...(1.8)$$

where $d$ = diameter of the restriction

D = inside diameter of the pipe.

#### 1.4.1.3 Reynolds Number

In practice, flow velocity at any cross section approaches zero in the boundary layer adjacent to the pipe wall and varies across the diameter. This flow velocity profile has a significant effect on the relationship between flow velocity and pressure difference developed in the head meters.

Sir Osborne Reynolds proposed single, dimensionless ratio known as Reynolds number, as a criterion to describe this phenomenon. This number, Re, is expressed as

$$R_e = \frac{\rho VD}{\mu} \quad ...(1.9)$$

where V = velocity

D = Diameter of the pipeline

$\rho$ = density and

$\mu$ = absolute viscosity.

Reynolds number expresses the ratio of inertial forces to viscous forces. At a very low Reynolds number, viscous forces predominate and inertial forces have little effect. At high Reynolds number, inertial forces predominate and viscous effects become negligible.

#### 1.4.1.4 Discharge Coefficient ($C_d$)

Discharge coefficient, C is defined as the ratio between actual volumetric flow rate and ideal volumetric flow rate.

$$C_d = \frac{q_{\text{actual}}}{q_{\text{ideal}}} \quad ...(1.10)$$

where $q_{\text{actual}}$ = Actual volumetric flow rate

$q_{\text{ideal}}$ = Ideal volumetric flow rate. (Theoretical)

#### 1.4.1.5 Flow Coefficient (K)

$$K = C_d / \sqrt{1 - \beta 4} \quad \text{...(1.11)}$$

where K = Flow coefficient

$C_d$ = discharge coefficient

$\beta$ = ratio of diameters = $d$/D

where $1/\sqrt{1-\beta 4}$ is known as velocity approach factor (that is velocity at section-A1) $M_{va}$.

$\therefore \quad K = C_d \cdot M_{va}$

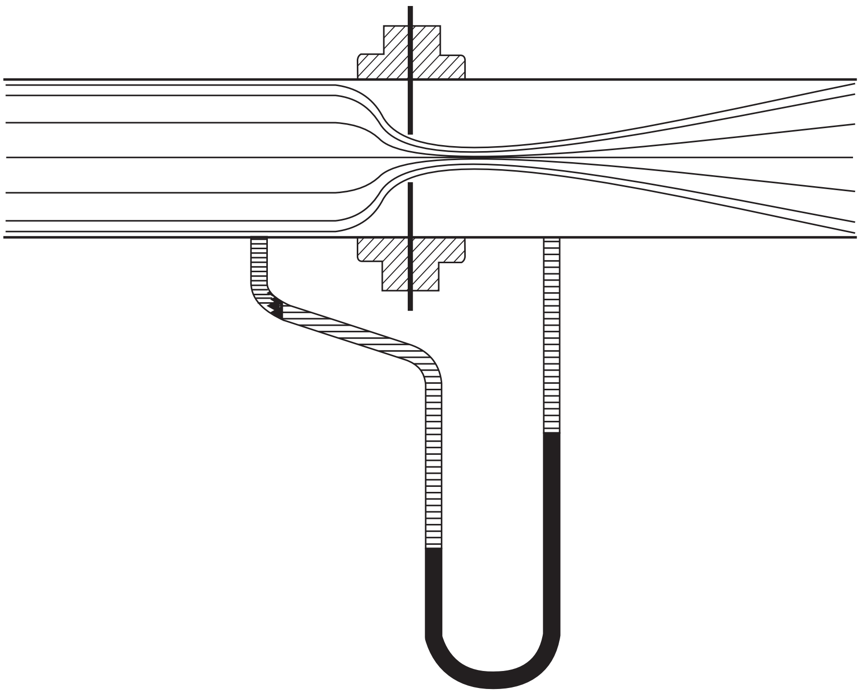


**Fig. 1.2** Orifice and Pressure-Differential Measurement

Measuring fluid flow with an orifice and differential pressure manometer as shown in Fig. 1.2, requires that the effect of the fluid over the manometer liquid be taken into account. Furthermore, the pressure differential at the orifice is usually expressed in liquid-column height. Then

$$P_1 - P_2 = (\rho_m - \rho_f)h \quad \text{...(1.12)}$$

where $h$ = differential at restriction, liquid column height

$\rho_m$ = weight density of manometer fluid

$\rho_f$ = weight density of fluid over the manometer fluid.

Finally if the flow rate is to be converted at the control room temperature at which the fluid density is $\rho_s$, then from equations (1.4), (1.11) and (1.12).

$$Q = KA_2 \sqrt{\frac{2gh\,(\rho_m - \rho_f)}{\rho} \cdot \frac{\rho}{\rho_s}} = KA_2 \sqrt{2gh} \sqrt{\frac{\rho(\rho_m - \rho_f)}{\rho_s}} \quad \text{...(1.13)}$$

### 1.4.1.6 Flow of Compressible Fluids in Pipes

If the fluid is compressible, a flow rate can be obtained if the gas is considered ideal and the flow is considered adiabatic.

The relation between pressure and velocity for flow of a compressible fluid through an orifice can be found from the law of conservation of energy as employed in thermodynamics. Assuming no heat flow to or from the fluid and no external work done on or by the fluid and neglecting the very small datum level difference ($Z_1 - Z_2$), we have

$$P_2 v_2 + \frac{V_2^{\,2}}{2g} + JE_2 = P_1 v_1 + \frac{V_1^{\,2}}{2g} + JE_1 \qquad ...(1.14)$$

where E = internal molecular energy of fluid

J = work equivalent of heat

$v$ = Specific volume of fluid

Employing the definition of enthalpy H gives

$$V_2^{\,2} - V_1^{\,2} = 2gJ\,(H_1 - H_2) \qquad ...(1.15)$$

For an ideal gas and if specific heats are constant,

$$H_1 - H_2 = \frac{KR}{J(K-1)}\, T_1\, [1 - (P_2/P_1)^{(K-1)/K}] \qquad ...(1.16)$$

where K = ratio of specific heats = $C_p/C_v$

R = gas constant for a given gas

T = absolute temperature.

From the equation of continuity (conservation of mass).

$$W = \frac{A_2 V_2}{v_2} = \frac{A_1 V_1}{v_1} \qquad ...(1.17)$$

where W is the mass flow rate.

Combining the foregoing equations and manipulating, we get the relation for flow of ideal gases.

$$W = A_1 \beta^2 \sqrt{\frac{2gK}{K-1} \cdot \frac{P_1}{v_1} \cdot \frac{(P_2/P_1)^{2/K} - (P_2/P_1)^{(K+1)/K}}{1 - \beta^4 (P_2/P_1)^{2/K}}} \qquad ...(1.18)$$

Manometer, however, measures ($P_1 - P_2$) and not $P_2/P_1$, therefore, it is necessary to convert the equation (1.18) such that W is a function of ($P_1 - P_2$). Write $P_2/P_1 = 1 - x$ such that $x = 1 - (P_2/P_1)$. In general, for gas flow $P_2/P_1$ is very close to unity such that $x$ is very close to zero.

Hence, $(P_2/P_1)^{2/K} \cong 1 - (2/K)\, x = 1 - (2/K) + (2/K)\,(P_2/P_1)$

$$(P_2/P_1)^{(K+1/K)} \cong 1 - (K + 1/K) + (K + 1/K)\,(P_2/P_1) \qquad ...(1.19)$$

using equation (1.19), equation (1.18) is modified to

$$w = CA_1 \beta^2 \; \frac{2g\,(P_1 - P_2)}{v_1\,[1 - \beta^4 (P_2/P_1)]^{2/k}} \qquad ...(1.20)$$

where C is the discharge coefficient.

For quick calculation an additional parameter known as the rational expansion factor Y is defined as

$$Y = \frac{\text{Compressible flow rate (mass)}}{\text{Incompressible flow rate (mass)}}$$

By determining the mass flow rate for incompressible fluids and multiplying with Y, flow rate for compressible fluids can be found out and Y can be easily shown as

$$Y = \sqrt{\frac{1-\beta^4}{1-\beta^4 (P_2/P_1)^{2/K}} \cdot \frac{K (P_2/P_1)^{2/K}}{K-1} \cdot \frac{1-(P_2/P_1)^{(K-1)/K}}{1-(P_2/P_1)}} \qquad \text{...(1.21)}$$

Instead of calculating Y from the equation (1.21) empirical relations are suggested which give good results for limited $(P_2/P_1)$ values, such as $0.8 \le 1.0$.

$$Y = 1 - [0.41 + 0.35\beta^4] (P_1 - P_2/KP_1) \qquad \text{...(1.22)}$$

When the gas contains moisture, as further correction is required to account correctly for the density of the vapour.

$$M = 1 + \frac{P_v \{(S_v/S) - 1\}}{P} \qquad \text{...(1.23)}$$

where $P_v$ = Vapour pressure (abs)

$S_v$ = Vapour specific gravity referred to air at the same pressure and temperature

S = Specific gravity of the gas

P = Pressure of the gas.

The specific volume of the gas may be found from

$$V = \frac{yRT}{P} \qquad \text{...(1.24)}$$

where $y$ = compressibility factor

R = gas constant

The flow equation for gases is

$$Q = KA_2Y \frac{v_b}{M_b} \sqrt{\frac{2gM_1(\rho_m - \rho_f)h}{v_1}} \qquad \text{...(1.25)}$$

where $v_b$ = Specific volume of gas at base condition

$v_1$ = specific volume of gas at upstream conditions

$M_1$ = Moisture factor at upstream conditions

$M_b$ = Moisture factor at base conditions.

## 1.4.2 Orifice Flow Meter

An Orifice flow meter is the most common head type flow measuring device. An orifice plate is inserted in the pipeline and the differential pressure across it is measured.

### 1.4.2.1 Principle of Operation

The orifice plate inserted in the pipeline causes an increase in flow velocity and a corresponding decrease in pressure. The flow pattern shows an effective decrease in cross section beyond the orifice plate, with a maximum velocity and minimum pressure at the venacontracta.

The flow pattern and the sharp leading edge of the orifice plate (Fig. 1.3) which produces it are of major importance. The sharp edge results in an almost pure line contact between the plate and the effective flow, with the negligible fluid-to-metal friction drag at the boundary.

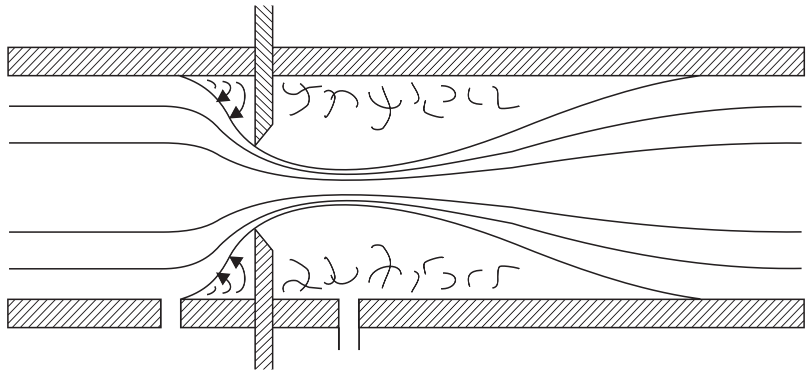


**Fig. 1.3** Flow pattern with orifice plate

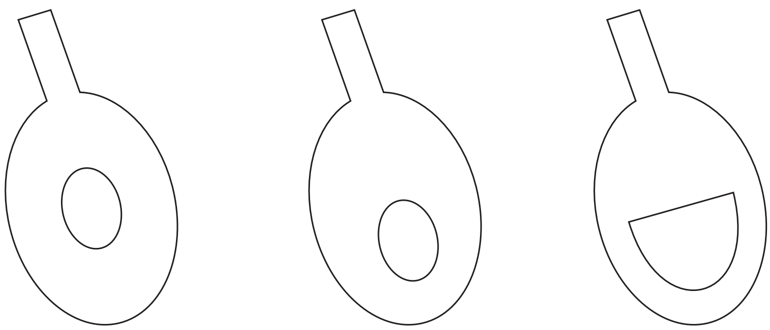
**1.4.2.2 Types of Orifice Plates**

The simplest form of orifice plate consists of a thin metal sheet, having in it a square edged or a sharp edged or round edged circular hole.

There are three types of orifice plates namely

1. Concentric
2. Eccentric and
3. Segmental type.

Fig. 1.4 shows two different views of the three types of Orifice plates.



(a) Concentric (b) Eccentric (c) Segmental

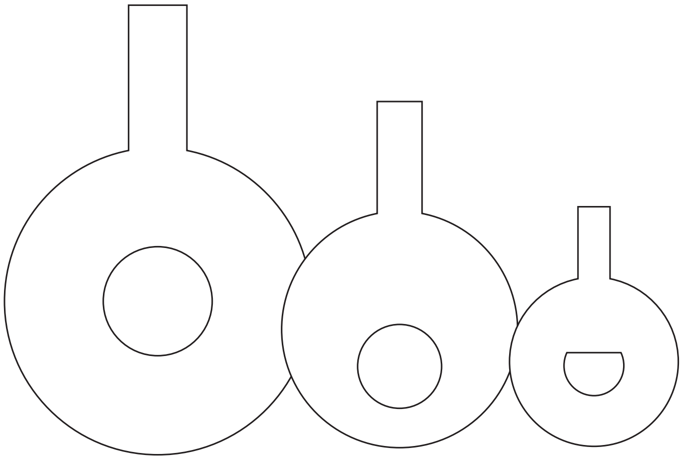



**Fig. 1.4** Sketch of orifices of different types

The concentric type is used for clean fluids. In metering dirty fluids, slurries and fluids containing solids, eccentric or segmental type is used in such a way that its lower edge coincides with the inside bottom of the pipe. This allows the solids to flow through without any obstruction. The orifice plate is inserted into the main pipeline between adjacent flanges, the outside diameters of the plate being turned to fit within the flange bolts. The flanges are either screwed or welded to the pipes.

**1.4.2.3 Machining Methods of Orifices**

Machining of the orifice plate depends on its specific use. Three types shown in Fig. 1.5 explains the machining methods.

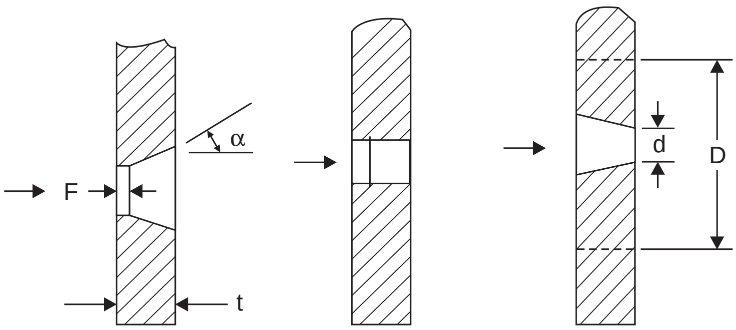



**Fig. 1.5** Machining Methods of Orifices

Types 1 and 2 are very commonly used and F is known as the plater. These two are easier to manufacture and are easily reproducible while type 3 is not. Thickness *t* as chosen to withstand the buckling forces. Type 1 has also reduced pressure losses. Type 3, known as the quadrant edged orifice, is used for more viscous fluids where corrections for low Reynolds number and viscosity are necessary.

### 1.4.2.4 Materials Chosen For Orifices

The material chosen for orifice plate is of any rigid material of non-rusting and non-corrodible. It is vital that the material should not corrode in the fluid being metered. Otherwise the edge of the orifice will get damaged to a sufficient extend to interfere with the character of the flow and the accuracy of the measurement. We should choose a material whose coefficient of Thermal expansion is known. The common materials used are Stainless steel, Monel, Phosphor bronze, Glass, Ceramics, Plastics, Brass, Copper, Aluminium and Tantalum.

### 1.4.2.5 Position of Taps in Orifice

The area of the fluid stream continues to contract after the stream has left the orifice and it has a minimum diameter at the venacontracta. The pressure of the fluid therefore continue to fall after leaving the orifice.

There is a slight fall in pressure in the approach section and the static pressure is at a minimum about one pipe diameter before the orifice plate. The pressure of the fluid then rises near the face of the orifice. There is then a sudden fall of pressure as the fluid passes through the orifice, but the minimum pressure is not attained until the venacontracta is reached. Beyond the venacontracta, there is a rapid recovery in the static pressure.

Owing to friction and dissipation of energy in turbulence, the maximum downstream pressure is always lesser than the upstream pressure. The pressure loss so caused depends upon the differential pressure and increases as the orifice ratio decreases for a given rate of flow.

The differential pressure obtained with an orifice plate will also depend upon the position of the pressure taps. The points to be observed while locating the taps are :

(*a*) they are in the same position relative to the plane of the orifice for all pipe sizes.

(*b*) the tap is located at a position for which the slope of the pressure profile is at least, so that slight errors in tap position will have less effort on the value of the observed pressure.

(*c*) the tap location in the installation is identical with that used in evaluation of the coefficients on which the calculation is based.

Fig. 1.6 shows the location of Pressure taps with Orifice plate.

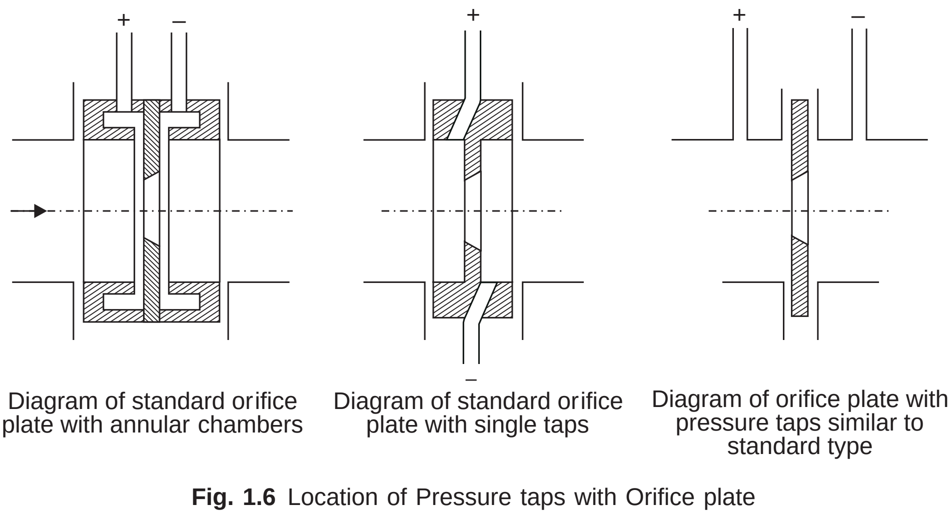



**Fig. 1.6** Location of Pressure taps with Orifice plate

There are five common locations for the differential pressure taps :

(*i*) Flange taps

(*ii*) Venacontracta taps

(*iii*) Radius taps

(*iv*) Full flow or pipe taps and

(*v*) Corner taps.

(*i*) **Flange taps.** They are predominantly used for pipe sizes 50 mm and larger and the centerlines are 25 mm from the orifice plate surface. They cannot be used for pipe size of less than 35 mm diameter. Since the venacontracta may be closer than 25 mm from the orifice plate.

(*ii*) **Venacontracta taps.** These taps use an upstream tap located one pipe diameter upstream of the orifice plate, and a downstream tap located at the point of minimum pressure. Venacontracta taps normally limited to pipe size 150 mm or large depending upon the flange rating and dimensions.

(*iii*) **Radius taps.** $d_1$ = D and $d_2$ = 1/2 D. These are similar to venacontracta taps except that downstream tap is located at one half pipe diameter. These are generally considered superior to the venacontracta tap because they simplify the pressure tap location dimensions and do not vary with changes in orifice β ratio.

(*iv*) **Pipe taps.** Pipe taps are located 2.5 pipe diameters upstream ($d_1$ = 2.5D) and 8 diameters downstream ($d_2$ = 8D) from the orifice plate. Because of the distance from the orifice, exact location is not critical, but the effects of pipe roughness, dimensional inconsistencies and so on are more severe.

(*v*) **Corner taps.** These taps are similar in many respects to flange taps, except that the pressure is measured at the 'Corner' between the orifice plate and the pipe wall. These are used for diameters of less than 50 mm.

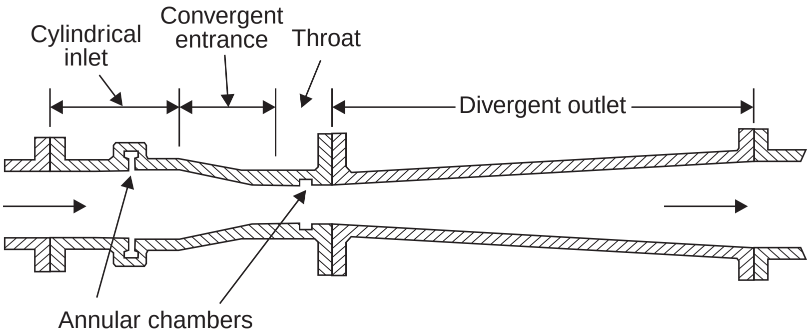
### 1.4.3 Venturi Tubes

Venturi tubes are differential pressure producers, based on Bernoulli's Theorem. General performance and calculations are similar to those for orifice plates. In these devices, there is a continuous contact between the fluid flow and the surface of the primary device.

#### 1.4.3.1 Classic Venturi Construction : [Long Form Venturi]

The classic Herchel Venturi tube is given in Fig. 1.7.

It consists of a cylindrical inlet section equal to the pipe diameter ; a converging conical section in which the cross sectional area decreases causing the velocity to increase with a corresponding increase in the velocity head and a decrease in the pressure head ; a cylindrical throat section where the velocity is constant so that the decreased pressure head can be measured ; and a diverging recovery cone where the velocity decreases and almost all of the original pressure head is recovered. The unrecovered pressure head is commonly called as head loss.




Classic Herschel venturi with annular pressure chambers

**Fig. 1.7** Classic Long form Venturi

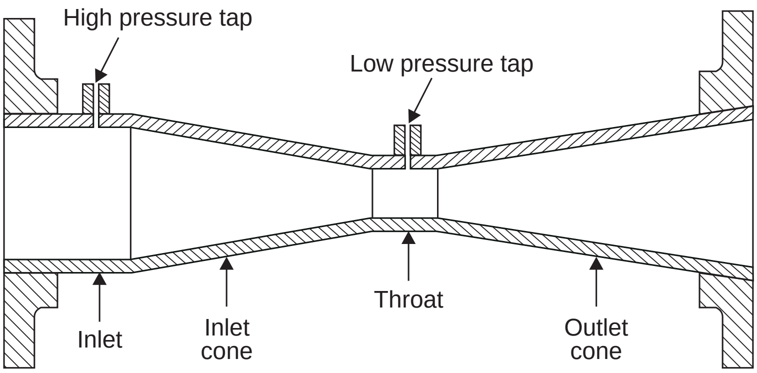
The classic venturi is always manufactured with a cast iron body and a bronze or stainless steel throat section. At the midpoint of the throat, 6 to 8 pressure taps connect the throat to an annular chamber so the throat pressure is averaged. The cross sectional area of the chamber is 1.5 times the cross sectional area of the taps. Since there is no movement of fluid in the annular chamber, the pressure sensed is strictly static pressure. Usually 4 taps from the external surface of the venturi into the annular chamber are made. These are offset from the internal pressure taps. It is through these taps that throat pressure is measured.

**Limitations**

This flow meter is limited to use on clean, non-corrosive liquids and gases, because it is impossible to clean out or flush out the pressure taps if they clog up with dirt or debris.

**1.4.3.2 Short Form Venturi Tubes**

In an effort to reduce costs and laying length, manufactures developed a second generation, or short-form venturi tubes shown in Fig. 1.8.




Short-form venturi tube

**Fig. 1.8** Short form Venturi

There were two major differences in this design. The internal annular chamber was replaced by a single pressure tap or in some cases an external pressure averaging chamber, and the recovery cone angle was increased from 7 degrees to 21 degrees. The short form venturi tubes can be manufactured from cast iron or welded from a variety of materials compatible with the application.

The pressure taps are located one-quarter to one-half pipe diameter upstream of the inlet cone and at the middle of the throat section. A piezometer ring is sometimes used for differential pressure measurement. This consists of several holes in the plane of the tap locations. Each set of holes is connected together in an annular ring to give an average pressure.

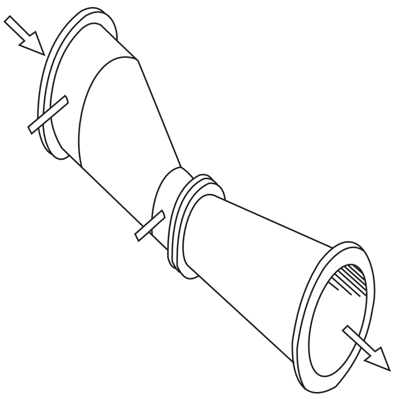
Venturis with piezometer connections are unsuitable for use with purge systems used for slurries and dirty fluids since the purging fluid tends to short circuit to the nearest tap holes. Piezometer connections are normally used only on very large tubes or where the most accurate average pressure is desired to compensate for variations in the hydraulic profile of the flowing fluid. Therefore, when it is necessary to meter dirty fluids and use piezometer taps, sealed sensors which mount flush with the pipe and throat inside wall should be used.

Single pressure tap venturis can be purged in the normal manner when used with dirty fluids. Because the venturi tube has no sudden changes in contour, no sharp corners, and no projections, it is often used to measure slurries and dirty fluids which tend to build up on or clog of the primary devices.

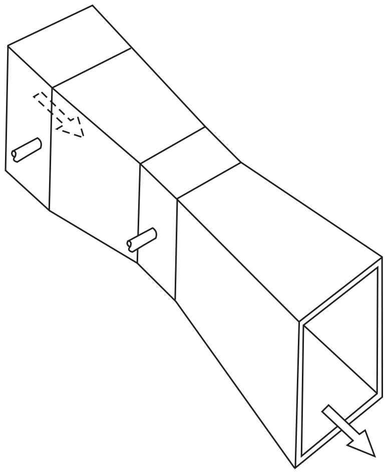
### 1.4.3.3 Types of Venturi Tubes

Venturis are built in several forms. These include

1. a standard long-form or classic venturi tube (Fig. 1.7)
2. a modified short form where the outlet cone is shortened (Fig. 1.8)
3. an eccentric form [Fig. 1.9 (*a*)] to handle mixed phases or to minimize buildup of heavy materials and
4. a rectangular form [Fig. 1.9 (*b*)] used in duct work.



(a) Eccentric type and



(b) Rectangular venturi type

**Fig. 1.9**

### 1.4.3.4 Installation of Venturi Tubes

A venturi tube may be installed in any position to suit the requirements of the application and piping. The only limitation is that with liquids the venturi is always full. In most cases, the valved pressure taps will follow the same installation guidelines as for orifice plates.

It is recommended that the use of straightening vanes upstream of the venturi to reduce the inlet pipe length. The vane installation should have a minimum of 2 diameters upstream and 2 diameters downstream before entering the venturi. There is no limitation on piping configuration downstream of the venturi except that a value should be no closer than 2 diameters.

## 1.4.4 Flow Nozzle

### 1.4.4.1 Flange Type Flow Nozzle

The Flow nozzle is a smooth, convergent section that discharges the flow parallel to the axis of the downstream pipe. The downstream end of a nozzle approximates a short tube and has the diameter of the venacontracta of an orifice of equal capacity. Thus the diameter ratio for a nozzle is smaller or its flow coefficient is larger. Pressure recovery is better than that of an orifice. Fig. 1.10 shows a flow nozzle of flange type.

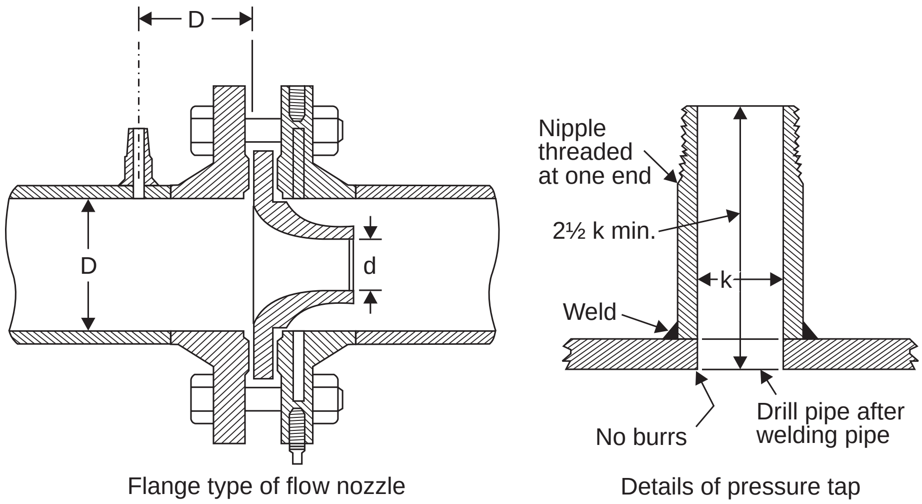



**Fig. 1.10** Flow nozzle

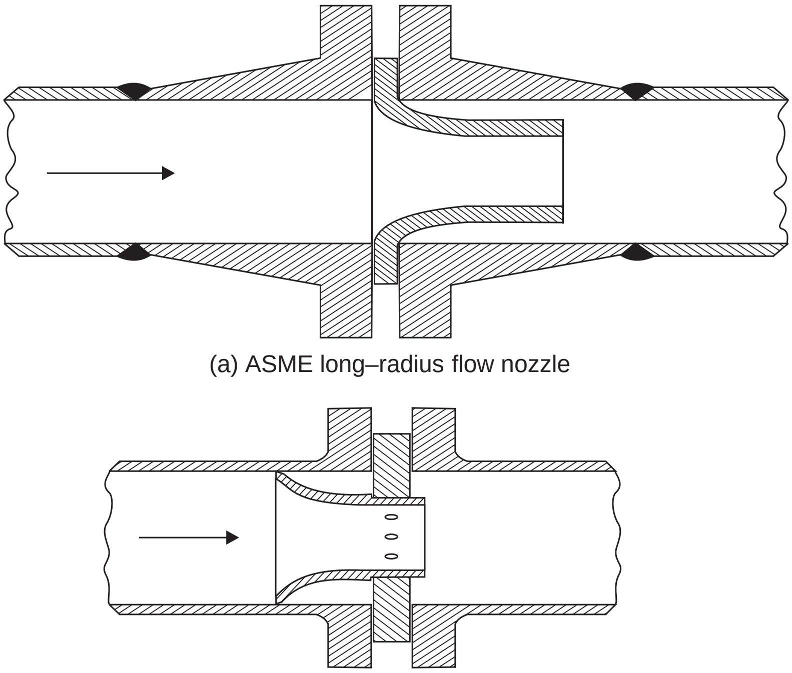
### 1.4.4.2 Different Designs of Flow Nozzle

There are different standard designs differing in details of the approach section and the length of the throat. Fig. 1.11 shows two accepted designs of flow nozzles.

Flow nozzles are usually made of gun metals, stainless steel, bronze or monel metal. They are frequently chromium plated. Sometimes slettite coating is provided to have abrasion resistance.

The pressure tappings may take the form of annular rings with slots opening into the main at each side of the flange of the nozzle or of single holes drilled through the flange of the main close to the nozzle flange.

It is not suitable for metering viscous liquids. It may be installed in an existing main without great difficulty.



(a) ASME long–radius flow nozzle

(b) Simplex type tg flow nozzole

**Fig. 1.11** (*a*) The ASME long-radius
(*b*) The Simplex type tg

#### 1.4.4.3 Advantages

1. Permanent pressure loss lower than that for an orifice plate.
2. It is suitable for fluids containing solids that settle.
3. It is widely accepted for high pressure and temperature steam flow.

#### 1.4.4.4 Disadvantages

1. Cost is higher than orifice plate.
2. It is limited to moderate pipe sizes.
3. It requires more maintenance. (It is necessary to remove a section of pipe to inspect or install it).

### 1.4.5 Dall Tube

#### 1.4.5.1 Construction And Working

It is a modified version of venturi tube. It produces large differential pressure with low pressure less than the conventional venturi tube. The photographic view and schematic sketch of the dall tube are shown in Fig. 1.12.

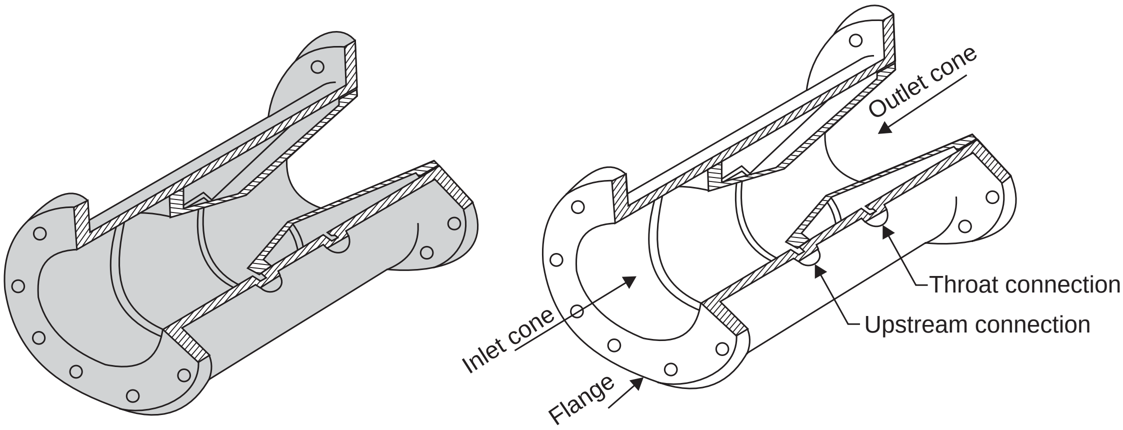



**Fig. 1.12** Dall Tube

It consists of a flanged spool piece body with a short, straight inlet section terminating in an abrupt decrease in diameter or inlet shoulder. This is followed by a conical restriction and a diverting outlet separated by a narrow annular gap. The high pressure tap is a hole drilled through the body tangent to the inlet shoulder. The low pressure tap is drilled through the body so as to connect with an annular slot in the throat. The inlet shoulder immediately proceeding the restriction has little effect on permanent pressure loss. The outlet cone causes a decrease in flow velocity that provides an increase in pressure recovery.

It is not suitable for measuring the flow of fluids containing solids which could settle out in the throat slot. The Dall tube is used for water, sewage, air and steam flow measurement. The Dall tubes are normally cast in gun metal. But for 450 mm and larger sizes, high grade cast iron is used. When it is required to protect the tube from corrosion, it may be lithcote lined.

#### 1.4.5.2 Advantages

1. Low head loss
2. Short lying length
3. It is available in numerous materials of construction.

#### 1.4.5.3 Disadvantages

1. Pressure difference is sensitive to up-stream disturbances.
2. More straight pipe required in the approach pipe length.
3. It is not considered for measuring flow of hot feed water.

### 1.4.6 Installation of Head Flowmeters

The head flow meter consists of a primary element such as an orifice, venturi, or pitot tube used with a differential pressure meter to measure the differential head caused by the flowing fluid at the primary element. The differential pressure meter may be any of the various meters such as the enlarged leg-mercury manometer, the bell gauge, the hollow gauge, the diaphragm gauge, the tilting U-type gauge or electronic differential pressure flow transmitters.

The differential-pressure meter and the primary element require careful connection and installation. It must be remembered that the meter is used for the purpose of measuring differential pressure. Any extraneous or false head introduced by the connecting piping causes a serious error.

### 1.4.6.1 Pressure Pipe Layout

Pressure piping is the pipe which connects the pipe tapping of the head producers to the meter or the differential pressure transducers. The important points to be carefully noted in laying the pressure piping in order to avoid the false readings are :

1. Condensation of water vapour in the case of air or gas, and
2. Air or vapour locks in the case of liquids and steam.

The following rules should be strictly followed in laying the pressure pipe, so as to avoid the above difficulties.

**Meter below the pipe**

If the meter or the differential transducer is to be located below the level of the main or pipe line in which the orifices is installed, the pressure pipe should be laid as follows.

**(a) Liquids and Steam**

Pressure pipes should fall continuously from orifice to meter at a slope of not less than 1/10 as shown in Fig. 1.13.

If the horizontal distance is too high to allow this slope by direct connection between the orifice and the meter, then pressure pipes may be first taken below the meter and then risen to the meter.

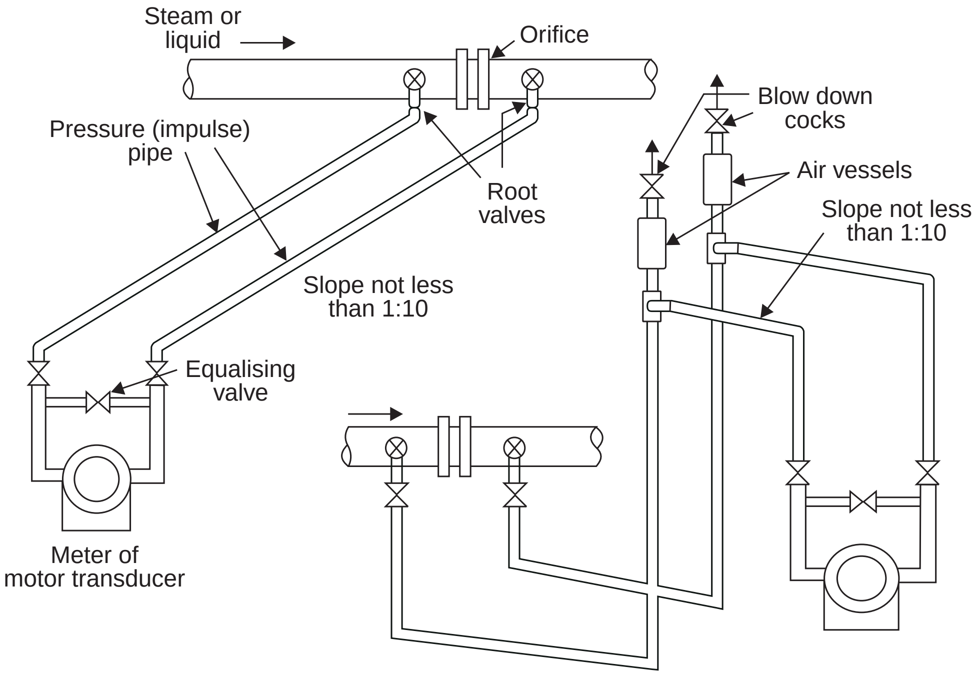



**Fig. 1.13** Pressure connections to meter below orifice for liquids and steam

**(b) Air and Gases**

The pressure pipe must first be raised above 0.5 m vertically up from the orifice as illustrated in Fig. 1.14 and then continuously fall at the slope of not less than 1 : 10 to the meter.

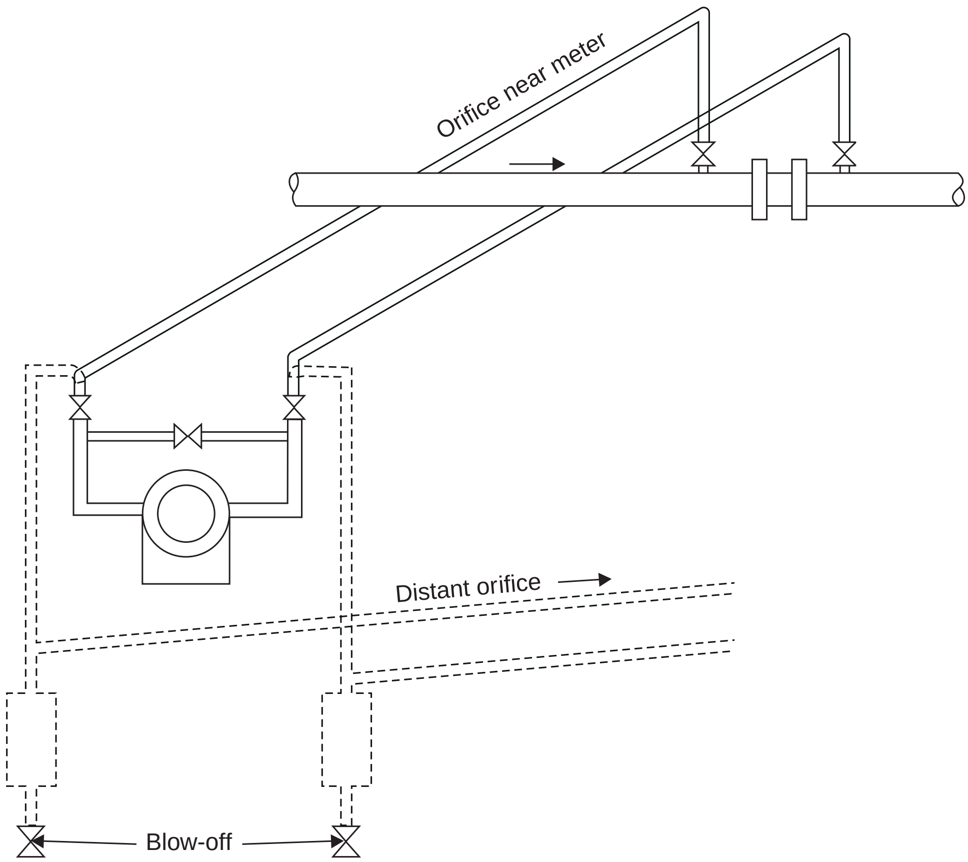



**Fig. 1.14.** Pressure connections to meter below orifice for Air and Gases.

**Meter above the pipe**

**(a) Liquids and Steam**

It may be noted that the special requirement for steam metering is the necessity of interposing cooling chambers for the purpose of condensing the steam and providing an adequate volume of water for supplying the meter displacement for all variations of load. With cooling chambers, the piping remains full of water and the steam does not act on the meter.

In this case, the pipe is first laid vertically downwards to a distance of about 0.5 m in order to minimise the possibility of entrance of air or gas from the main, and the pipe is raised continuously at a slope of not less than 1 : 10 to the meter. The meter is fitted with air vessels as shown in Fig. 1.15

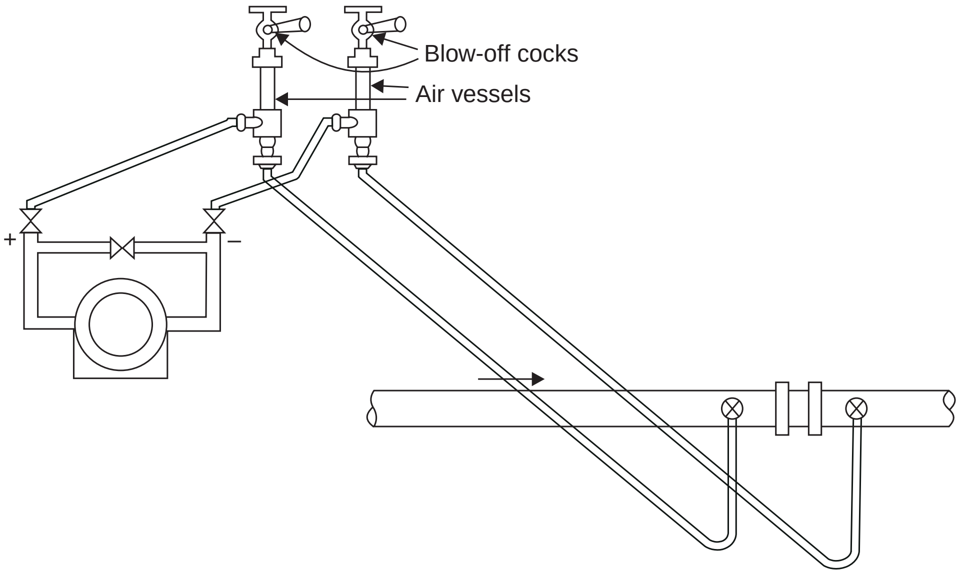



**Fig. 1.15** Pressure connections to meter above orifice for liquids and steam

### (b) Air and Gases

The impulse pipe is continuously raised at a slope of not less than 1 : 10 from orifice to meter as shown in Fig. 1.16. The pressure pipes should be fitted with sumps at the lowest points, and the sumps should be drained at suitable intervals, which is already shown in the Fig. 1.14.

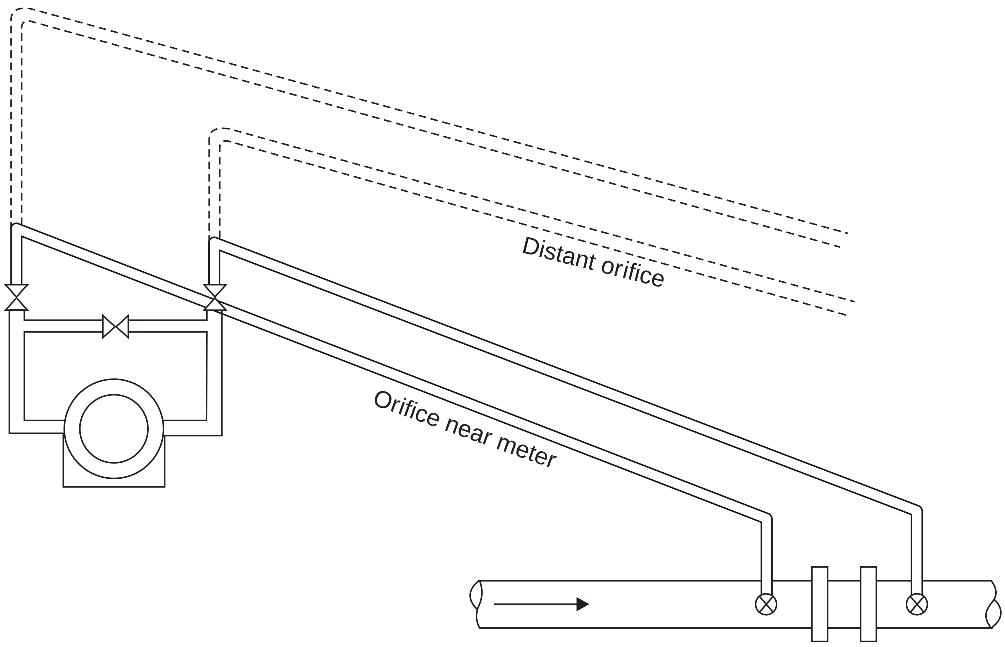



**Fig. 1.16** Pressure connections to meter above orifice for air and gases

**1.4.6.2 Installation of condensation Pots**

Condensation pots should be used when flow rate of steam is to be measured by means of differential pressure transmitters. The condensation pots secure smooth column of condensate in both the impulse lines connecting the differential pressure transmitters.

Four types of condensation pots are manufactured to suit the various pressure ranges.

(*i*) Made of cast iron for pressure upto 16 kg/cm$^2$

(*ii*) Made of carbon steel for pressure upto 64 kg/cm$^2$

(*iii*) Made of stainless steel for pressure above 64 kg/cm$^2$ and below 100 kg/cm$^2$.

(*iv*) Made of molybdenum steel for pressure upto 200 kg/cm$^2$.

In the case of vertical steam mains, it is essential that both the condensation pots placed at the level of the upper orifice connection. Its installation is illustrated in Fig. 1.17.

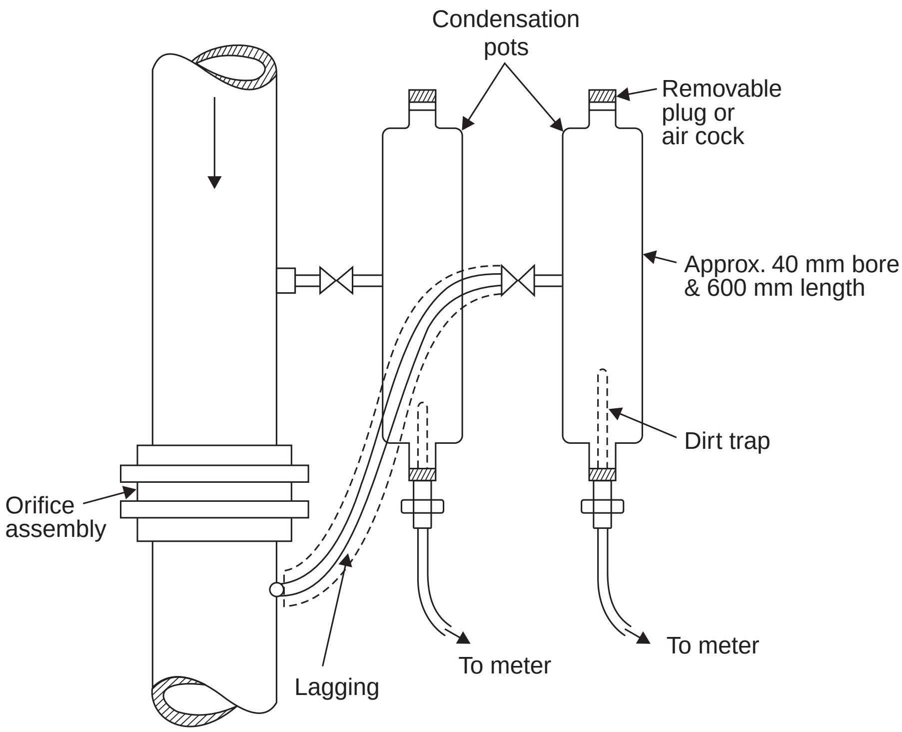



**Fig. 1.17** Installation of Condensation pots

A leg of large bore is used to convey the pressure from the lower connection to the appropriate condensation pot. The bore should not be less than 14 mm throughout. If possible, for obtaining better results, this pipe may be run in contact with the main within the main lagging.

**1.4.6.3 Installation of Sealing Pots**

Sealing pot is intended for protecting primary instruments like, pressure gauges, pressure or differential pressure transmitters etc. from the influences of chemically aggressive medium under measurement.

They are also used in the metering of oils or tarry liquids, which are of low viscosity in the mains due to high temperature ; but owing to atmospheric cooling in pressure pipes these become viscous and as such make meter sluggish in response.

The sealing pots transmit the orifice pressures to a second and less viscous liquid, the separating surfaces occurring in parallel bore of the sealing vessels and serving as friction less pistons. These are usually connected very close to the mains. The sealing liquid must be non-corrosive and immiscible with the fluid to be metered. It should preferably be of moderately low viscosity such as transformer oil, spindle oil, kerosene, paraffin oil, glycerine etc.

Fig. 1.18 shows how installation of sealing pot is being made.

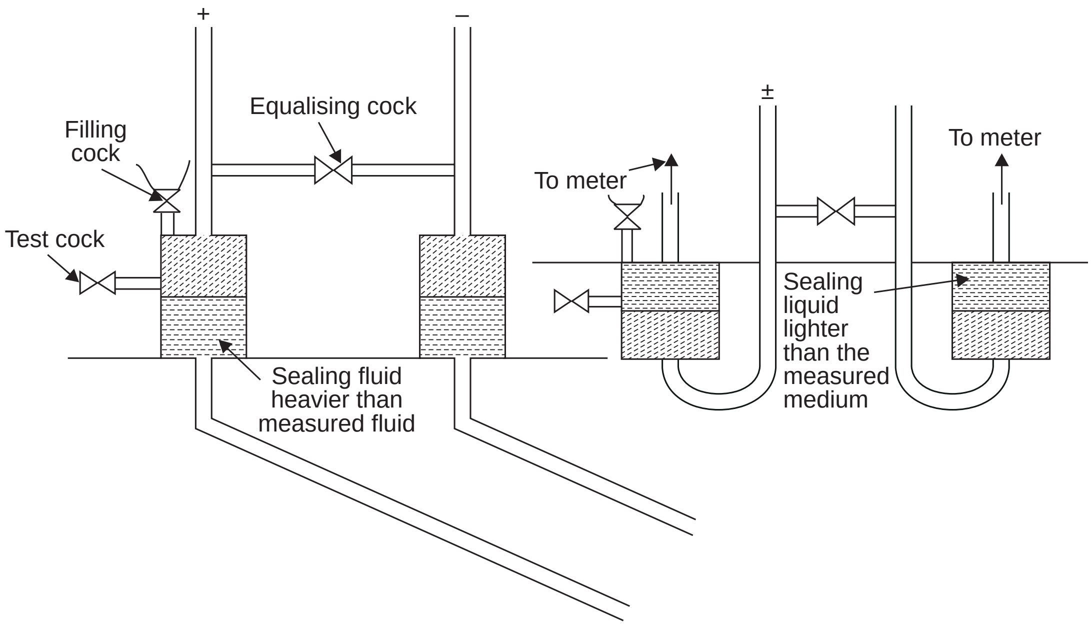



**Fig. 1.18** Installation of Sealing pots

### 1.4.6.4 Factors to be Considered in Piping Arrangement

The factors for selecting proper piping arrangement are listed below considering only the important ones :

1. The piping arrangement must be absolutely free of leaks.
2. The connecting lines must be clean and free from obstructions. Use as few fittings as possible.
3. The connecting lines must pitch a 50 mm to prevent gas packets and drainage.
4. The connecting lines should not be more than 15 m long, preferably less.
5. The connecting lines must be maintained at a temperature between 0 and 50°C.
6. The differential—pressure meter should be installed below the level of the primary element if possible.

7. Drain legs should be installed at the meter when dirt and sediment exist in the connecting lines.
8. Condenser chambers used for steam lines must be in level.
9. Sealing chambers used for corrosive fluids must be in level and should be vented.

The proper connections for several examples are given in Fig. 1.19

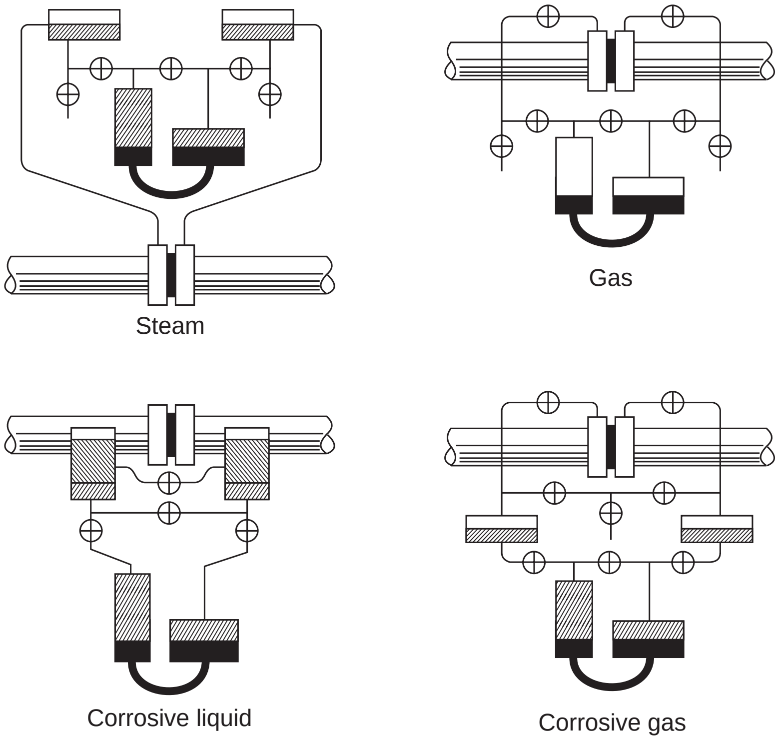



**Fig. 1.19** Installation of Orifice Head meters

Fig. 1.19 shows the arrangements for different mediums for accurate measurement. If the pipe is tapped at the bottom, any solid matter flowing in the line might choke the tap. If the pipe is tapped at the top, any dissolved gas might escape through the tap and reach the manometer upsetting the true reading. Generally, recommended taps are at the side of the pipe. The pipes are arranged so that in case of an eventuality the meter can be removed without much difficulty. Large chambers containing sealing liquids are mounted in the pipe lines so that the liquid does not come in contact with the manometric fluid. These chambers are known as sealing pots, and sealing liquids are chosen such that they do not mix with the process fluid or the manometric fluid and are unaffected by them. The sealing liquids commonly chosen are ethylene glycol, glycerin, dibultyl phthalate, chloro naphthalene and chlorinated oils. Generally the sealing fluid should be heavier than the flowing fluid. The sealing chambers are generally half filled through filling plugs with visual checks such as gauge glasses.

### 1.4.7 Pitot Tube

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

#### 1.4.7.1 Principle

Consider Fig. 1.20 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.

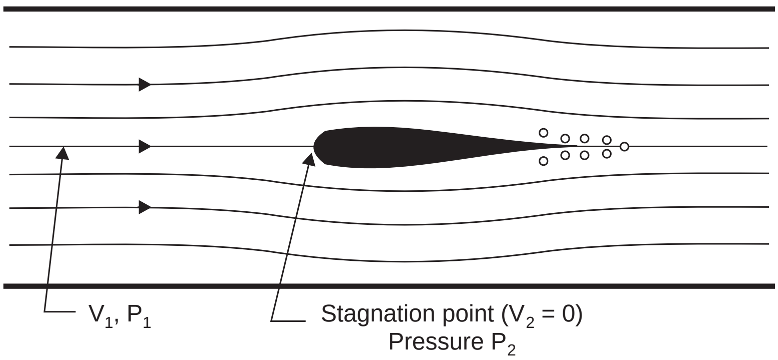



**Fig. 1.20** Flow around a solid body

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.

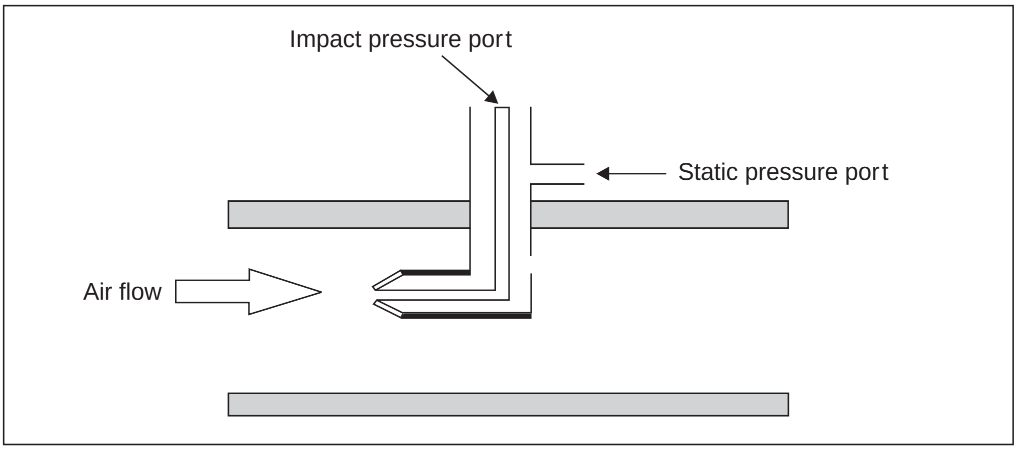



**Fig. 1.21** A common industrial type pitot tube

A common industrial type of pitot tube consists of a cylindrical probe inserted into the air stream, as shown in Fig. 1.21. 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

$$v = Cp\sqrt{2gh} \quad ...(1.26)$$

where C$p$ is the pitot tube constant.

Fig. 1.22 shows a typical pitot tube which also shows the taps for sensing static pressure.

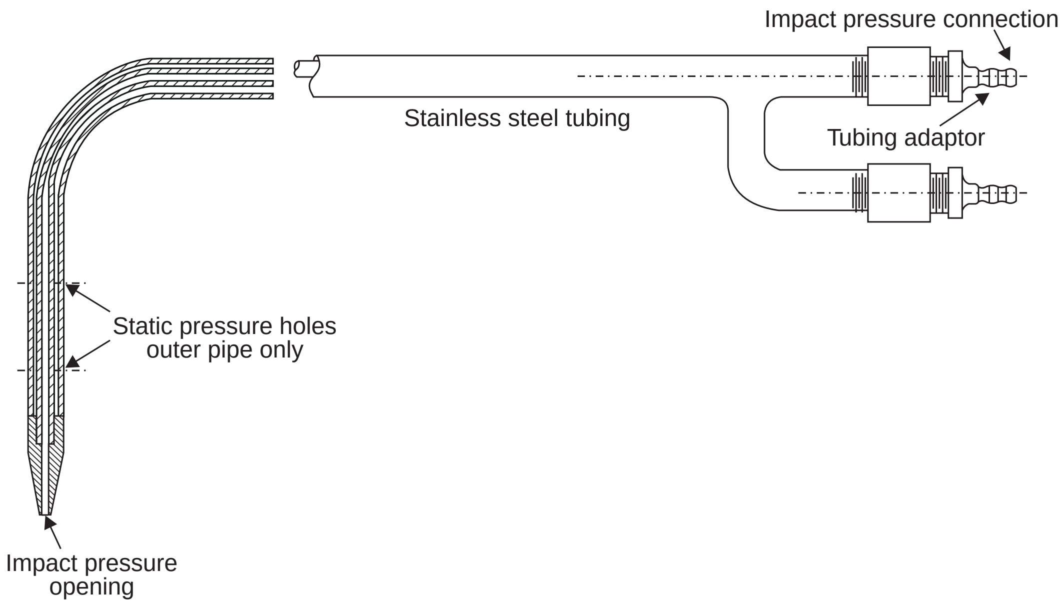



**Fig. 1.22** Typical pitot tube

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.

#### 1.4.7.2 Averaging Pitot Tube (Annubar)

To obtain a better average value of flow, special two-chamber flow tubes with several pressure openings distributed across the stream are available, as shown in Fig. 1.23. These annular averaging elements are called annubars. They consist of a tube with high- and low-pressure holes with fixed separations.

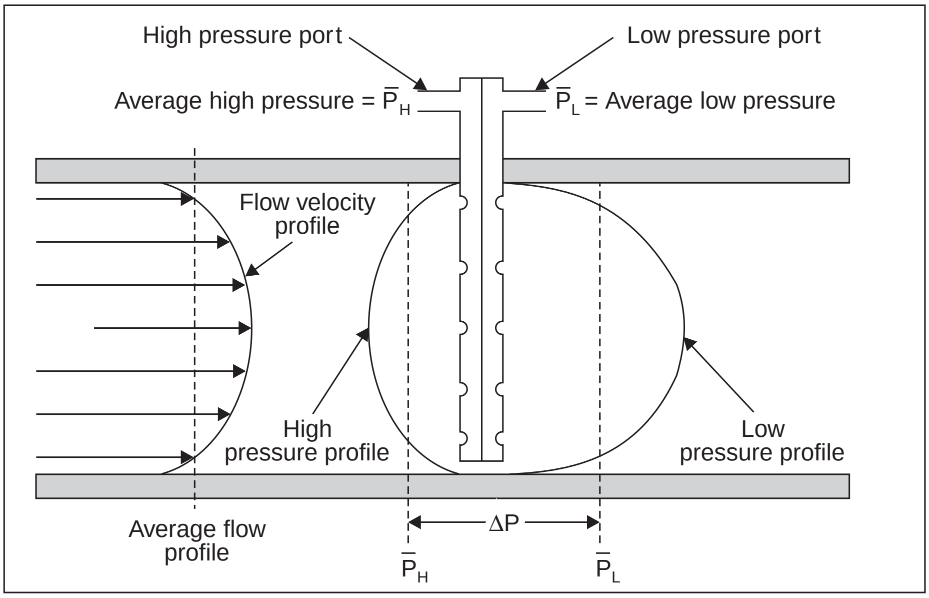



**Fig. 1.23** Averaging pitot tube (Annubar)

An annubar flow sensor produces a differential pressure (ΔP) signal that is the algebraic difference between the average value of the high-pressure signal (P*h*) and low-pressure single (P*l*) as shown in the above Fig. 1.23.

A high-pressure profile is produced by the impact of the flow velocity profile on the upstream side of the sensing tube. Inside the high-pressure chamber, an average high-pressure signal is obtained by correctly placing the sensing ports in the tube. The flow that passes through the sensor creates a low-pressure profile. This pressure profile is sensed by downstream ports directly behind the high-pressure ports. Working on the same principle as the high-pressure side, an average low pressure signal is produced in the low-pressure chamber.

#### 1.4.7.3 Advantages

1. No pressure loss.
2. It is relatively simple.
3. It is readily adapted for flow measurements made in very large pipes or ducts.

#### 1.4.7.4 Disadvantages

1. Poor accuracy.
2. Not suitable for dirty or sticky fluids and fluids containing solid particles.
3. Sensitive to upstream disturbances.

### 1.4.8 Differential Pressure Transmitters

The high performance differential pressure transmitter can be used to measure liquid, gas or steam flow. It outputs a 4 to 20 mA DC signal corresponding to the measured differential pressure.

In the variable head producers, the relationship between the flow rate and the differential head produced is expressed as

$$Q \propto \sqrt{h} \qquad \text{...(1.27)}$$

As the above relationship is non-linear, it is necessary to make the current of the transmitters as a linear one. For the purpose of linearising the current, the square root extractor, which may be built-in or externally added, is used.

Fig. 1.24 shows the photographic view of high performance differential pressure transmitter. Fig. 1.25 shows the differential pressure transmitter with built-in square root extractor and Fig. 1.26 shows the differential pressure transmitter with external square root extractor.

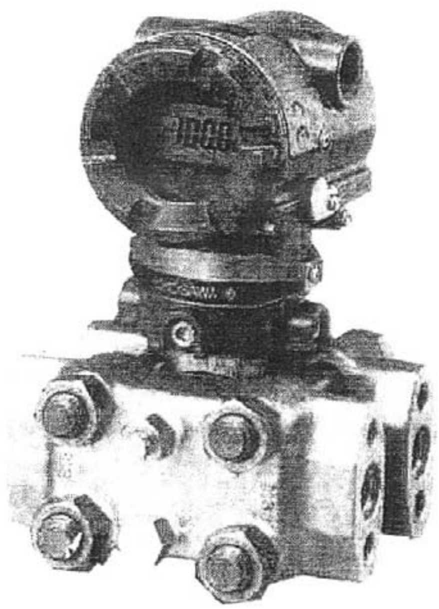


**Fig. 1.24** High performance differential Pressure transmitter.

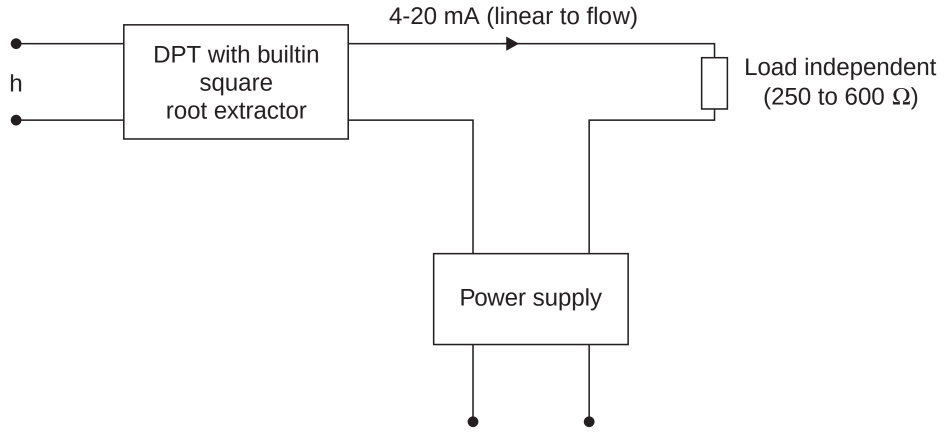



**Fig. 1.25** Differential Pressure transmitter with built-in square root extractor.

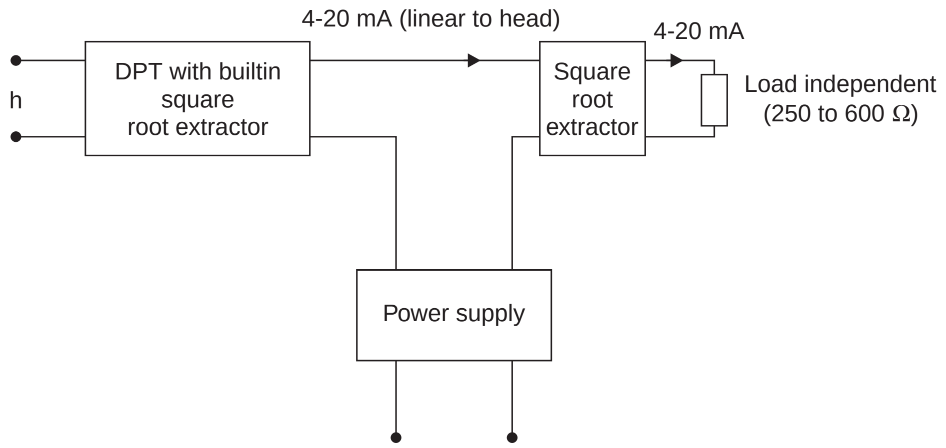



**Fig. 1.26** Differential Pressure transmitter with external square root extractor.

Fig. 1.27 shows the relationship between the power supply voltage and External load resistance.

Differential pressure transmitters normally require a DC voltage supply of 12 V to 42 V and connected to various other circuits using two wires only. They are called two wire transmitters. Sometimes the output signal is passed through a standard resistor, also called a conditioning resistor, of 250 Ω to convert the 4-20 mA current signal into 1-5V DC voltage signal. The load independency of such a standard transmitter may vary from 600 Ω to 1500 Ω. Improved version of such transmitters are called as “Smart transmitters” with computer compatibility. It has flexibility to meet existing analog and emerging digital requirements. It offers the familiarity of an analog transmitter with built-in BRAIN or HART (Highway Addressable Remote Transducer) capability digital smart communication. Remote calibration, span changing, zero adjustment are also possible.

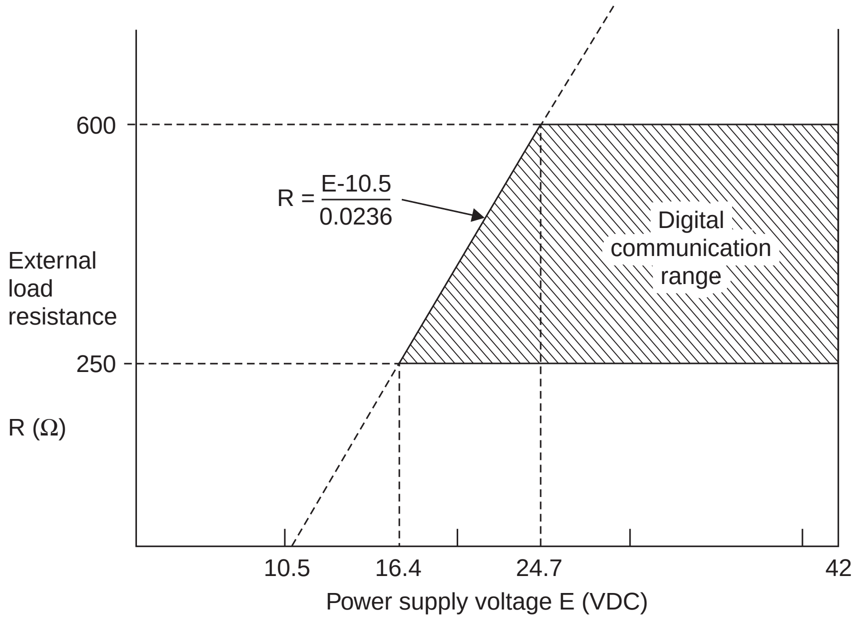



**Fig. 1.27** Relationship between power supply voltage and external load resistance

Though the input signal conditioning circuits are different for different inputs, the main amplifier, output circuit and communication facilities are same. Hence a transmitter can be used for universal inputs. When combined with the HART communicator, it permits programming input signals, spans, and parameters through two-way communication.

### 1.4.9 Quantity Meters

Quantity meters are used for the measurement of low flow rates in industries. These meters operate by passing the fluid to be measured through the meter in separate and distinct increments of alternately filling and emptying containers of known capacity. The number of times the container is filled and emptied gives the quantity of flow.

#### 1.4.9.1 Positive Displacement Meters

Positive displacement type flow meters are generally used for accurate measurement of steady flow. These flow meters are working under the following principle.

Positive displacement meters split the flow of liquids into separate known volumes based on the physical dimensions of the meter, and count them or totalize them. They are mechanical meters in that one or more moving parts, located in the flow stream, physically separate the fluid into increments. Energy to drive these parts is extracted from the flow stream and shows up as pressure loss between the inlet and the outlet of the meter. The general accuracy of these meters is dependent upon minimizing clearances between the moving and stationary parts and maximizing the length of the flowing path. For this reason, accuracy tends to increase as size increases.

Positive displacement meters may be divided into following categories :

(*i*) Nutating disc type.

(*ii*) Reciprocating piston type.

(*iii*) Oval gear type and

(*iv*) Helix type.

**1.4.9.1.1 Nutating Disk Type**

This meter, also known as disk meter, is used extensively for residential water service. The moving assembly, which separates the fluid into increments consists of an assembly of a radially slotted disk with an integral ball bearing and an axial pin. Fig. 1.28 shows the nutating disk type meter.

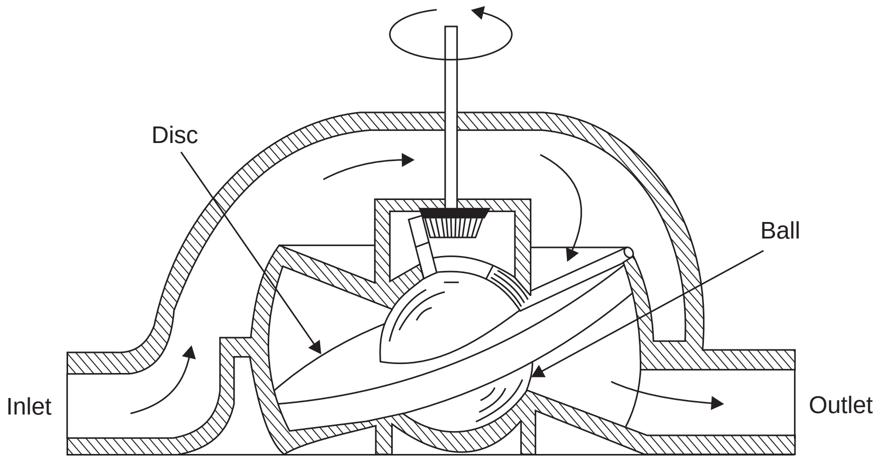



**Fig. 1.28** Nutating disk meter

This part fits into and divides the metering chamber into four volumes, two above the disk on the inlet side and two below the disk on the outlet side. As the liquid attempts to flow through the meter, the pressure drop from inlet to outlet causes the disk to wobble or nutate, and for each cycle to display a volume equal to the volume of the metering chamber minus the volume of the disk assembly. The end of the axial pin, which moves in a circular motion, drives a cam that is connected to a gear train and the totalizing register.

Inaccuracy : ± 1 to 2%.

Temperature range : – 150 to 120°C.

Max working pressure : 10 kg/cm$^2$.

**1.4.9.1.2 Reciprocating Piston Meter**

In the reciprocating piston meter shown schematically in Fig. 1.29, the reciprocating piston passes the liquid alternately through each end of the cylinder from the inlet to the outlet and also the slide valve which controls the inlet and outlet ports and operates the counter. A number of piston operations on a center crank are generally incorporated in this type of meter. For low flow, the differential pressure is small, for which large diameter pistons and small piston strokes are chosen with minimum of friction. Accuracy of this flow meter is within 0.5%.

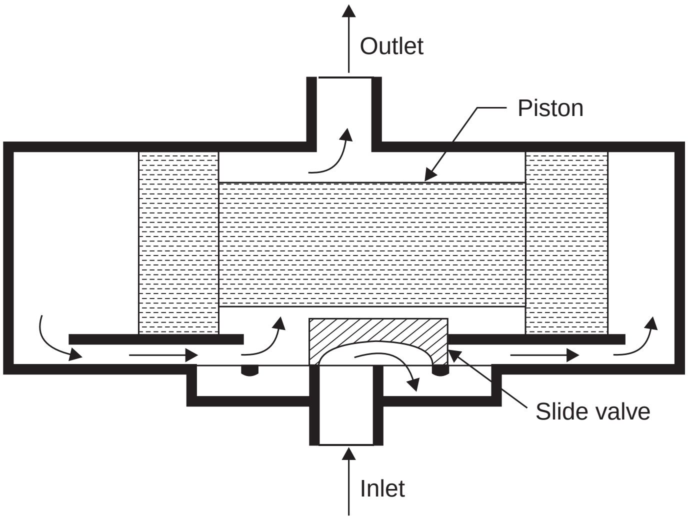



**Fig. 1.29** Operating Principle of the Piston meter

**1.4.9.1.3 Oval—Gear Flow Meters**

A special variety of the rotating tube flow meter is the oval – geared metering elements. These oval-geared meters are generally used on very viscous liquid, which is difficult to measure using other flow meters. In this design, as shown in Fig. 1.30, a precise volume of liquid is captured by the gap formed between housing and the gear.

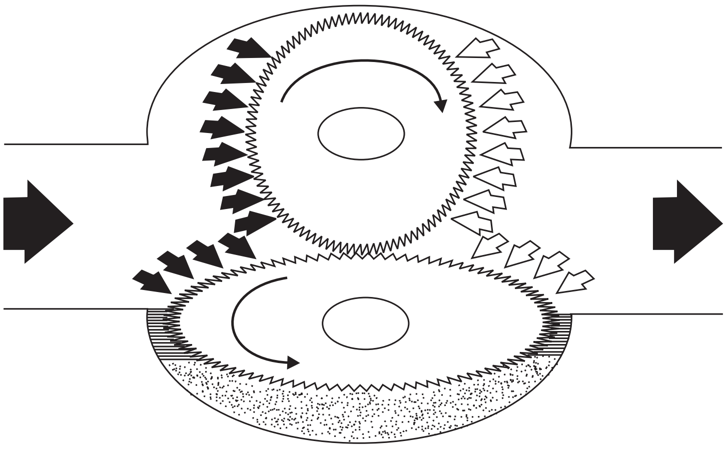


**Fig. 1.30** Oval-gear flow meter

To explain the operation in detail, let us consider the Fig. 1.31.

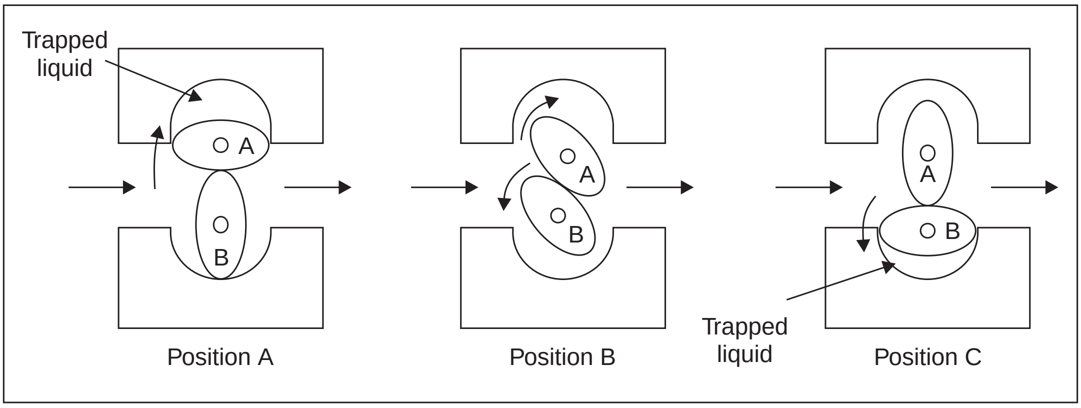



**Fig. 1.31** Working principle of Oval-gear flow meter

In position A, uniform forces are applied equally on the top and bottom of oval gear B, so that the gear does not rotate. Rotor A has entrapped a known volume of liquid between the rotor and the meter body, and there is a balanced force on the bottom of the gear. However, there is a force on the bottom of gear A, causing it to rotate clockwise (CW). This causes gear B to rotate in a counter clock wise (CCW) direction to position B.

In position B, fluid enters the space between gear B and the meter body, as the fluid that was entrapped between gear A and the body simultaneously leave the area of entrapment. The higher upstream pressure oppose the lower downstream pressure at the ends of gear A and gear B, which makes gear A and gear B continue to rotate in CW and CCW directions respectively, to position C.

In position C, a known amount of fluid has been entrapped between gear B and the meter body. This operation is then repeated, with each revolution of the gears representing the passage of four times the amount of fluid that fills the space between the gear and the meter body. Therefore, the fluid flow is directly proportional to the rotational velocity of the gears.

If slippage between the oval-gears and the housing is small, and the flow rate and viscosity are high, these flow meters can provide high accuracies. (0.1%).

These flow meters are available in the sizes suitable for 6 mm to 400 mm diameters pipelines. Their materials of construction include brass, carbon steel, and 316 stainless steel. Operating pressures are available up to 100 kg/cm$^2$ and temperatures up to 300°C.

**1.4.9.1.4 Helix Type Flow Meters**

The Helix flow meter is a positive displacement device utilizing two uniquely nested, radically pitched helical rotors as the measuring elements. Close machining tolerances ensure minimum slippage and thus high accuracy. Fig. 1.32 illustrates the photographic view of a helix type flow meter.

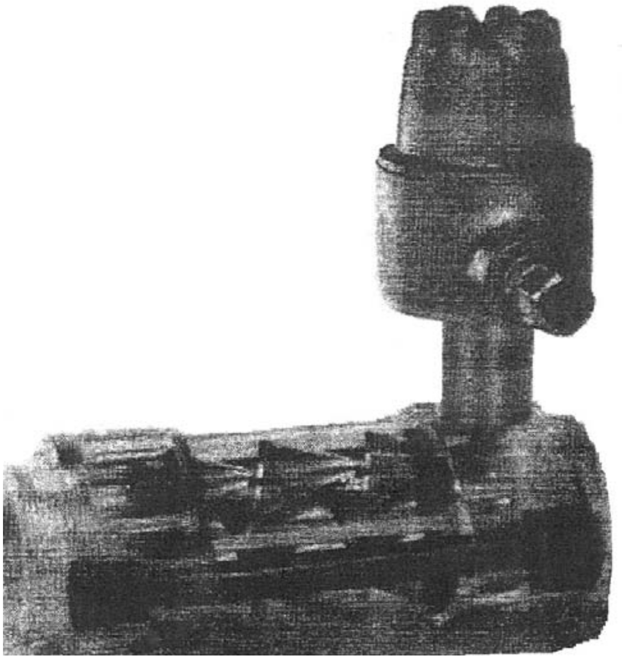


**Fig. 1.32** Viscous Helix flow meter

### 1.4.10 Inferential Flow Meters

In the inferential type of flow metering techniques, the out quantity flow rate is inferred from a characteristic effect of a related phenomenon. Turbine flow meters, variable area flow meters and target flow meters are some of the types of inferential flow meters.

#### 1.4.10.1 Turbine Flow Meters

**Principle**

The turbine flow meter is mainly used for the purpose of measurement of liquid and gas at very low flow rates. A simple turbine flow meter shown in Fig. 1.33, provides a frequency

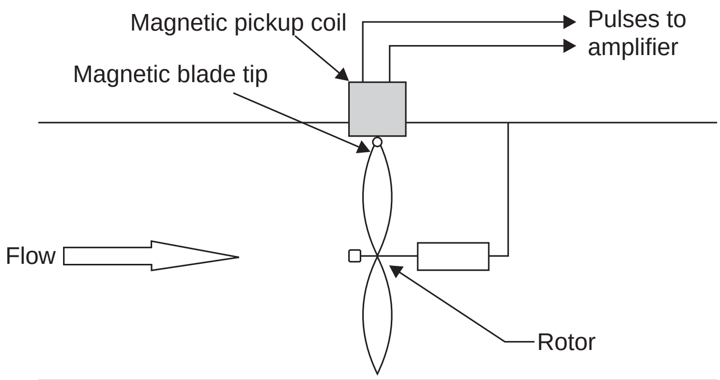



**Fig. 1.33** A simple Turbine Flow meter

output signal that varies linearly with volumetric flow rate over specified flow ranges. The entire fluid to be measured enters the flow meter, then passes through a rotor. The fluid passing through the rotor causes it to turn with an angular velocity that is proportional to the fluid linear velocity. Therefore, the volumetric flow rate is linear within the given limits of flow rate.

Let us consider a typical Turbine flow meter shown in Fig. 1.34, which consists of a multibladed rotor (turbine wheel) which is mounted at right angles to the axis of the flowing fluid. The rotor is supported by ball or sleeve bearings on a shaft which is retained in the flow meter housing by a shaft-support. The rotor is rotating freely about its axis.

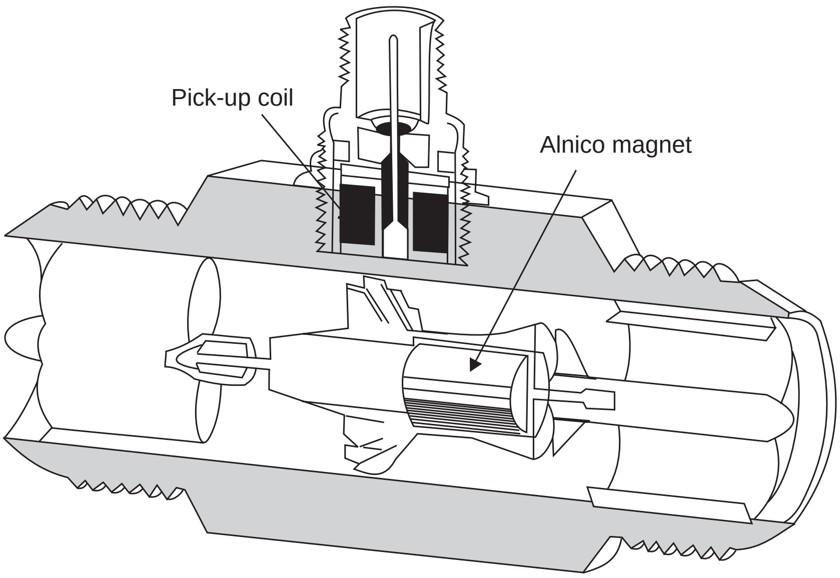



**Fig. 1.34** Turbine Flow meter

**Working**

The flowing fluid impinges on the blades of turbine (rotor), imparting a force to the blade surface which causes the rotation of the rotor. At a steady rotational speed, the speed of the rotor is directly proportional to the fluid velocity, and hence to volumetric flow rate. The speed of rotation is monitored in most of the meters by a magnetic pick-up coil, which is fitted to the outside of the meter housing. The magnetic pick-up coil consists of a permanent magnet with coil windings which is mounted in close proximity to the rotor but external to the fluid channel. As each rotor blade passes the magnetic pick-up coil, it generates a voltage pulse which is a measure of the flow rate, and the total number of pulses give a measure of the total flow. By digital techniques, the electrical voltage pulses can be totalled, differenced and manipulated so that a zero error characteristic of digital handling is provided from the electrical pulse generator to the fluid readout.

The number of pulses generated is given as

$$n_p = \frac{T_p f}{Q} \qquad \text{...(1.28)}$$

where $n_p$ = pulses per volume unit

$T_p$ = time constant in minutes

Q = Volumetric flow rate

$f$ = frequency in Hz.

The turbine meters are available in sizes ranging from 6.35 mm to 650 mm and liquid flow ranges from 100 cubic centimeter to over 50 cubic meters.

**Advantages**

1. Better Accuracy [± 0.25% to ± 0.5%].
2. It provides excellent repeatability [± 0.25% to ± 0.02%] and rangeability (10 : 1 and 20 : 1).
3. It has fairly low pressure drop.
4. It is easy to install and maintain.
5. It has good temperature and pressure ratings.
6. It can be compensated for viscosity variation.

**Disadvantages**

1. High cost.
2. It has limited use for slurry applications.
3. It is not suitable for non-lubricating fluids.
4. They cannot maintain its original calibration over a very long period and therefore periodical recalibration is necessary.
5. They are sensitive to changes in the viscosity of the liquid passing through the meters.
6. They are sensitive to flow disturbances.
7. Due to high bearing friction is possible in small meters, they are not preferred well for low flowrates.

**Applications**

The turbine meters are widely used for military applications. They are particularly useful in blending systems for the petroleum industry. They are effective in aerospace and air borne applications for energy-fuel and cryogenic flow measurements.

**1.4.10.2 Variable Area Flow Meters**

**Basic Principle**

In the orifice meter, there is a fixed aperture and flow is indicated by a drop in differential pressure. In area meter, there is a variable orifice and the pressure drop is relatively constant. Thus, in the area meter, flow is indicated as a function of the area of the annular opening through which the fluid must pass. This area is generally readout as the position of a float or obstruction in the orifice.

The effective annular area in area meter is nearly proportional to height of the float, plummet or piston, in the body and relationship between the height of float and flow rate is approximately linear one with linear flow curve as well as scale graduations.

**Types of Variable Area Flow Meters**

Area meters are of two general types :

1. Rotameters and
2. Piston type meter.

**Rotameters.** In this meter, a weighted float or plummet contained in an upright tapered tube, is lifted to the position of equilibrium between the downward force of the plummet and the upward force of the fluid in addition to the buoyancy effect of the fluid flowing past the float through the annular orifice. The flow rate can be read by observing the position of the float.

**Piston Type Meter.** In this meter, a piston is accurately fitted inside a sleeve and is lifted by fluid pressure until sufficient post area in the sleeve is uncovered to permit the passage of the flow. The flow is indicated by the position of the piston.

Fig. 1.35 shows the types of Variable area flow meter (*a*) Rotameter and (*b*) Piston Type meter.

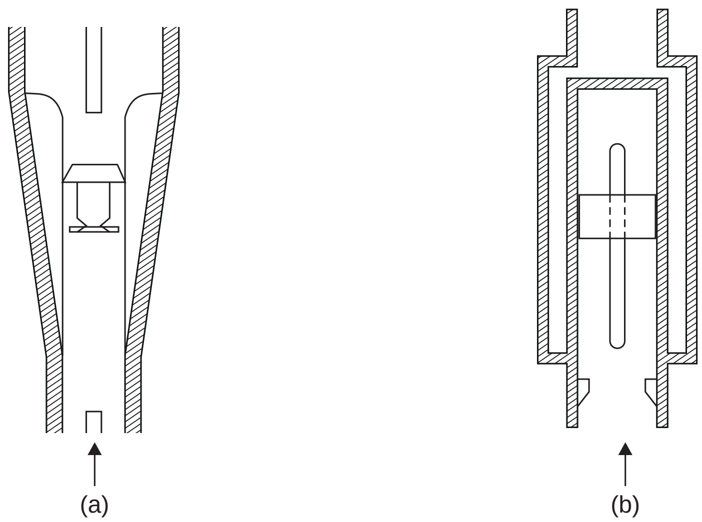



**Fig. 1.35** Types of Variable area flow meter (*a*) Rotameter (*b*) Piston Type meter

**Performance Characteristics**

**1. Linearity.** The flow rate (volume) through a variable area meter is essentially proportional to the area and, as a result, most of these meters have essentially equal-scale increments. A typical indicating rotameters scale is non linear by about 5%.

**2. Differential.** An important characteristic of the variable area meter is that the pressure loss across the float is a constant. The overall differential across the meter will increase at higher flow rates because of friction losses through the fittings.

**3. Accuracy.** The most common accuracy is ±2% of full scale reading. This increases considerably with individual calibration and scale length. Repeatability is excellent.

**4. Capacity.** Variable area flow meters are the most commonly used means for measuring low-flow rates. Full scale capacities range from 0.5 $cm^3$/min of water and 30 std $cm^3$/min of air in the smallest units to over 1200 litres/min of water and 1700 $m^3$/h of air in 8 cm height meters.

**5. Minimum Piping Requirement.** An area meter usually can be installed without regard to the fittings or lengths of straight pipe proceedings or following the meter.

**6. Corrosive or Difficult to handle liquid.** These can often be handled successfully in an area meter. They include such materials as oil, tar, refrigerants, sulphuric acid, black liquor, beverages, aqua regia and molten sulphur. In general, if the nature of the fluid does not permit the use of a conventional differential pressure type meter because the fluid is dirty, viscous or corrosive, certain area meters have an advantage over other types of meters.

**7. Pressure Drop.** By placing very light floats in over sized meters, flow rates can be handled with a combination of very low pressure loss (often 2.5 cm of water column or less) and 10 : 1 flow range.

**Basic Equations**

The following flow equations are developed based primarily on liquids. However, the resultant working equations can be used equally well on gas service.

The variable area meter shown in Fig. 1.36 consists of a tapered metering tube and a float which is free to move up and down within the tube. The metering tube is mounted vertically with the small end at the bottom. The fluid to be measured enters at the bottom of the tube, passes upward around the float, and out at the top.

When there is no flow through the meter, the float rests at the bottom of the metering tube where the maximum diameter of the float is approximately the same as the bore of the tube. When fluid enters the metering tube, the buoyant effect of the fluid lightens the float, but it has a greater density than the liquid and the buoyant effect is not sufficient to raise it. There is a small annular opening between the float and the tube. The pressure drop across the float increases and raises the float to increase the area between the float and tube until the upward hydraulic forces acting on it are balanced by its weight less buoyant force. The metering float is 'floating' in the fluid stream. The float moves up and down in the tube in proportion to the fluid flow rate and the annular area between the float and the tube. It reaches a stable position in the tube when the forces are in equilibrium.

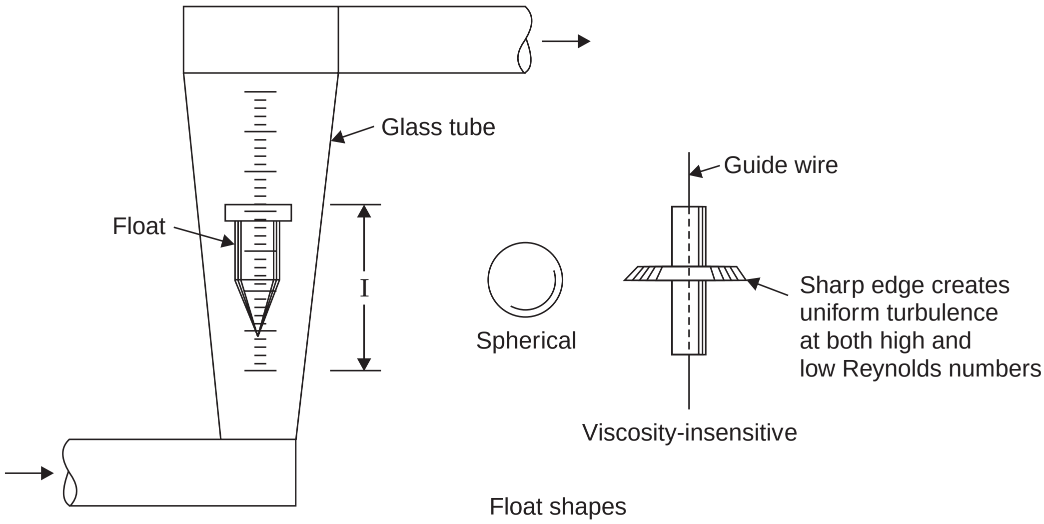



**Fig. 1.36** Fundamental operation of a variable area flow meter

With upward movement of the float towards the larger end of the tapered tube, the annular opening between the tube and the float increases. As the area increases, the pressure differential across the float decreases. The float assumes a position, in dynamic equilibrium, when the pressure differential across the float plus the buoyancy effect balances the weight of the float. Any further increase in flow rate causes the float to rise higher in the tube ; a decrease in flow causes the float to drop at a lower position. Every float position corresponds to one particular flow rate and no other for a fluid of a given density and viscosity. It is merely necessary to provide a reading or calibration scale on the tube and flow rate can be determined by direct observation of the position of the float in the metering tube. Definitions of the terms in the following analysis are written reference to Fig. 1.36. According to Bernoulli's theorem :

$$V_2 - V_1 = \sqrt{2g(h_1 - h_2)} \qquad ...(1.29)$$

where $V_1$ = velocity of fluid at section-1

$V_2$ = velocity of fluid at section-2

$g$ = acceleration due to gravity

$h_1$ = hydraulic head at section-1

$h_2$ = hydraulic head at section-2

The hydraulic head drop is expressed in terms of pressure drop as

$$\frac{h_1 - h_2}{\rho} = P_1 - P_2 \qquad ...(1.30)$$

where $P_1$ = Pressure at section-1

$P_2$ = Pressure at section-2

$\rho$ = specific weight of fluid

The continuity of flow equation may be written as

$$Q = A_2 V_2 \rho \qquad ...(1.31)$$

where $Q$ = Flow

$A_2$ = Area at section-2

To allow for factors not included in this analysis, however, a factor $C_d$, called the coefficient of discharge, is introduced. Then Equation (1.31) becomes

$$Q = C_d A_2 V_2 \rho \quad \text{...(1.32)}$$

Neglecting $V_1$ in Equation (1.29) and combining Equation (1.29) and (1.32), the expression becomes

$$Q = C_d A_2 \sqrt{2g\gamma (P_1 - P_2)} \quad \text{...(1.32A)}$$

Dropping $V_1$ from Equation (1.29) is justified on the basis that the area $A_1 >> A_2$, causing $V_1 << V_2$.

To express the flow in volumetric units, since $q = Q/\gamma$, Equation (1.33) becomes

$$q = C_d A_2 \sqrt{\frac{2g(P_1 - P_2)}{\rho}} \quad \text{...(1.32B)}$$

where $q$ = flow in volumetric unit.

From the force equation at equilibrium condition,

$$P_1[\pi D_f^2/4] + V_f \rho = P_2 [\pi D_f^2/4] + V_f \rho_f \quad \text{...(1.33)}$$

where $D_f$ and $\rho_f$ are the diameter and density of float

from the equation (1.33), $P_1 - P_2 = V_f (\rho_f - \rho) [4/\pi D_f^2]$ ...(1.33A)

by substituting $P_1 - P_2$, flow $q$ can be calculated as

$$q = C_d \frac{D_p^2 - D_f^2}{D_f} \sqrt{\frac{\pi g V_f (\rho_f - \rho)}{2\rho}} \qquad \left[\because \ A_2 = \frac{\pi}{4}(D_p^2 - D_f^2)\right] \quad \text{...(1.37)}$$

**Rotameter-Elements**

The term "Rotameter" was derived from the fact that floats originally were produced with slots to give them rotation for the purpose of centering and stabilizing the float.

The essential elements of any rotameter are listed as follows. In addition to suitable inlet and outlet connections, they comprise (1) a metering tube and (2) a float.

**1. Metering Tubes.** In modern practice, they are formed on a mandrel and annealed to prevent internal stresses so that strong, uniform tubes result. This method also permit the forming of tubes with greater reproducibility and interchangeability and forming special shapes, such as non conical tubes with curved elements designed to spread out the graduations at the lower end of the range. It is possible to modify the conical form slightly in order to give the exact linear relationship between aperture and float position which is not quite achieved with a purely conical tube.

The most important special shape is a modified conical section having internal beading or lands which serve to guide the float. Fig. 1.37 shows some types of glass rotameter tubes with ribs or beads for float guides.

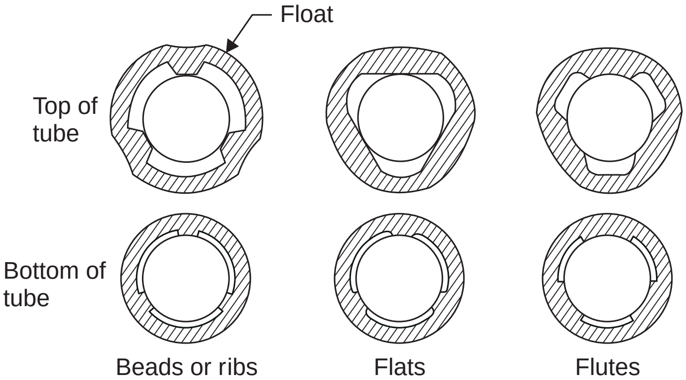



**Fig. 1.37** Several types of glass rotameter tubes with ribs or beads for float guides

**2. Floats.** Floats can be made from several materials to obtain corrosion resistance or capacity modification. Ratings are generally in terms of meter capacity, using a stainless steel float. It has been found that the float shape determines to a large extend of how much a rotameter will be influenced by changes in the viscosity of the measured fluid. Floats having sharp edges have been found to be relatively insensitive to viscosity changes over a considerable viscosity range. Some typical float shapes are shown in Fig. 1.38.

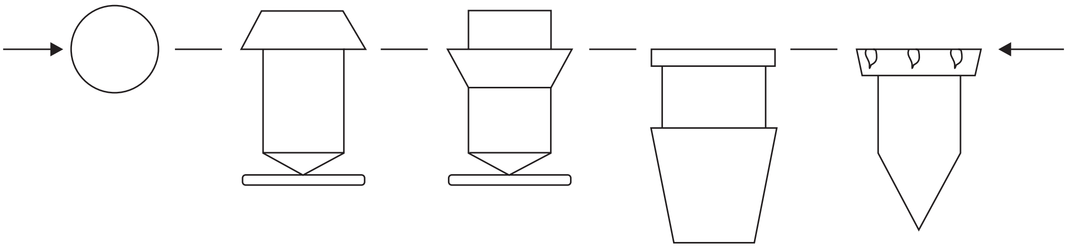


**Fig. 1.38** Partial representation of typical rotameter float shapes

**Advantages**

1. Low cost.
2. Low pressure drop.
3. Rangeability is better.
4. It is suitable for small flow rates.
5. It is easily equipped with alarms and switches or any transmitting devices.
6. It also measures the flow rate of corrosive fluids.
7. There is an availability of viscosity-immune floats.
8. It can be used in some light slurry services.

**Disadvantages**

1. It is difficult to handle the glass tube type.
2. It must be mounted vertically.
3. It is not suitable for pulsating services.

4. Generally it is limited to small pipe services.
5. It is limited to low temperatures.
6. Accuracy is = ± 1/2 to 10%.
7. It requires in-line mounting.

**1.4.10.3 Target Flow Meters**

**Principle of Working.** Material buildup in front of orifice plates can cause both measurement errors and plugging when the process stream is a liquid slurry or a gas carrying wet solids. The annular orifice, which is illustrated in Fig. 1.39 was introduced to solve this problem by providing an annular opening for the solids to pass through. Target flow meters are similar in design except that the pressure taps have also been eliminated and the detection of differential pressure been replaced by force measurement. Both of these designs are suited for dirty or low turbulence flow metering applications, if high precision is not required.

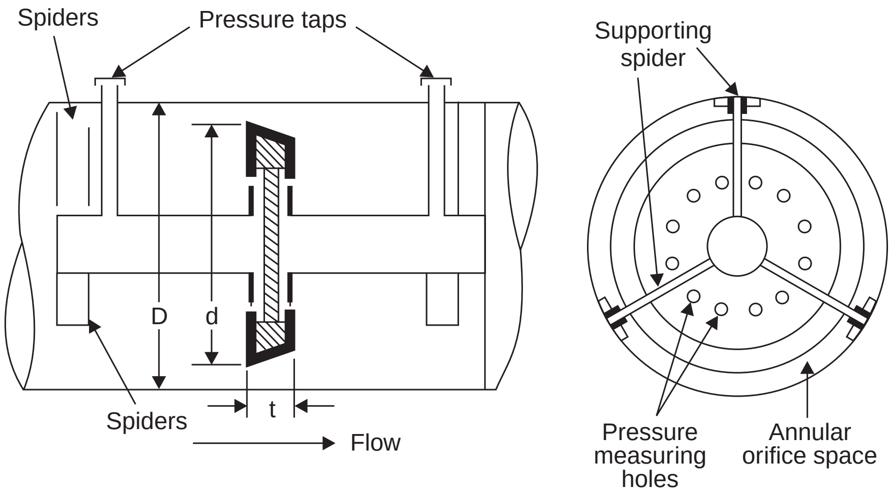



**Fig. 1.39** Annular orifice plate installation

**Construction.** The target meter combines in a single unit an annular orifice and a force-balance transducer. Output is either an electric or pneumatic signal proportional to the square of the flow. Target meters are available in sizes from 1/2 to 8 inch pipe diameter. The annular orifice is formed by a circular disk supported in the center of a tubular section having the same diameter. Flow through the open ring between disk and tube develops a force on the disk proportional to velocity head (the square of the flow). The disk is mounted on a rod passing out through a flexible seal. The force on the disk is measured from the rod outside the seal, using a standard force-balance transducer integrally mounted on the flow tube.

**Applications.** The target meter is applied in a number of fields for measurement of liquids, vapours and gases. It allows unimpeded flow of condensates and extraneous material along the bottom of a pipe and at the same time allows unimpeded flow of gas or vapour along the top of the pipe.

Operating temperature range : 300° C.

Operating pressures : 15 kg/cm$^2$.

Targets with diameters of 0.6, 0.7 and 0.8 times tube diameter are available. Overall accuracy of calibrated target meters is better than that of orifice-type systems.

## 1.4.11. Mass Flow Meters

The knowledge of mass flow rates is necessary in combustion fuel control, in reactor recipe formulations and in many other applications, from mining and dredging to food, pulp and paper, pharmaceuticals and the chemical industry.

### 1.4.11.1 Angular-Momentum-Type Mass Flow Meters

The principle of angular momentum can be described by referring to Newton's second law of the angular motion and the definition of angular momentum, using the following notation :

H = angular momentum

I = moment of inertia

$\omega$ = angular velocity

$\alpha$ = angular acceleration

T = torque

$r$ = radius of gyration

$m$ = mass

$t$ = time

Newton's second law of angular motion states that

$$T = I\alpha \quad ...(1.35)$$

and defines that $$H = I\omega \quad ...(1.36)$$

But, Since by definition $$I = mr^2 \quad ...(1.37)$$

Now equation (1.35) becomes $$T = mr^2\alpha \quad ...(1.38)$$

and equation (1.36) becomes $$H = mr^2\omega \quad ...(1.39)$$

Since $$\alpha = \omega/t \quad ...(1.40)$$

equation (1.38) becomes $$T = m/t\ r^2\omega \quad ...(1.41)$$

Solving for mass flow rate, $m/t$, we get

$$m/t = T/r^2\omega \quad ...(1.42)$$

Also, dividing both sides of equation (1.39) by $t$

$$H/t = m/t\ r^2\omega \quad ...(1.43)$$

Since torque is in terms of force, the right-hand side of equation (1.42) must be multiplied by $g$ (9.8 m/sec$^2$) to obtain a dimensionally correct equation. Therefore, since $r^2$ is a constant for any given system, the flow of fluid can be determined if an angular momentum is introduced into the fluid stream and measurements are made of the torque produced by this angular momentum and of the fluid's angular velocity.

#### 1.4.11.2 Constant-Torque-Hysteresis Clutch

Another angular-momentum type mass flow meter eliminates the necessity of making a torque measurement after imparting a constant torque to the fluid stream. The relationship between mass flow and torque is

$$\frac{m}{t} = \frac{T}{r^2 \omega} \qquad ...(1.44)$$

Therefore, if T is held at a constant value, and since $r^2$ is a physical constant of any given system,

$$\frac{m}{t} = \frac{k}{\omega} \qquad ...(1.45)$$

This relationship is used in designing a mass flow meter as follows : A synchronous motor is placed in the center of the flow meter assembly. This motor is magnetically coupled to an impeller which is located within the flowing process stream. The magnetic coupling between the motor and the impeller is provided by means of a hysteresis clutch which transmits a constant torque from the motor to the impeller. Thus, a measurement of the rotational speed of the impeller is inversely proportional to the mass flow rate.

#### 1.4.11.3 Impeller-Turbine Mass Flow Meters

Fig. 1.40 shows an impeller turbine mass flow meter.

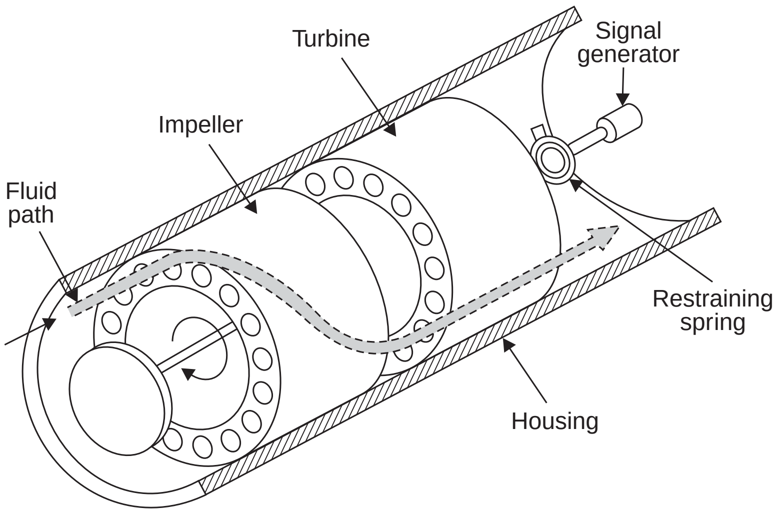



**Fig. 1.40** Impeller turbine mass flow meter

The impeller, turbine-type mass flow meter uses two rotating elements in the fluid stream, an impeller and a turbine. Both elements contain channels through which the fluid flows. The impeller is driven at a constant speed by a synchronous motor through a magnetic coupling and imparts an angular velocity to the fluid as it flows through the meter. The turbine located downstream of the impeller removes all angular momentum from the fluid and thus receives a torque proportional to the angular momentum. This turbine is restrained by a spring which deflects through an angle which is proportional to the torque exerted upon it by the fluid, thus giving a measure of mass flow.

**1.4.11.4 Twin-Turbine Mass Flow Meter**

Another angular-momentum-type device is the twin turbine mass flow meter. In this instrument two turbines are mounted on a common shaft.

Fig. 1.41 shows a twin-turbine mass flow meter in which two turbines are connected with a calibration torsion member. A reluctance type pick up is mounted over each turbine and a strong magnet is located in each turbine within the twin-turbine assembly.

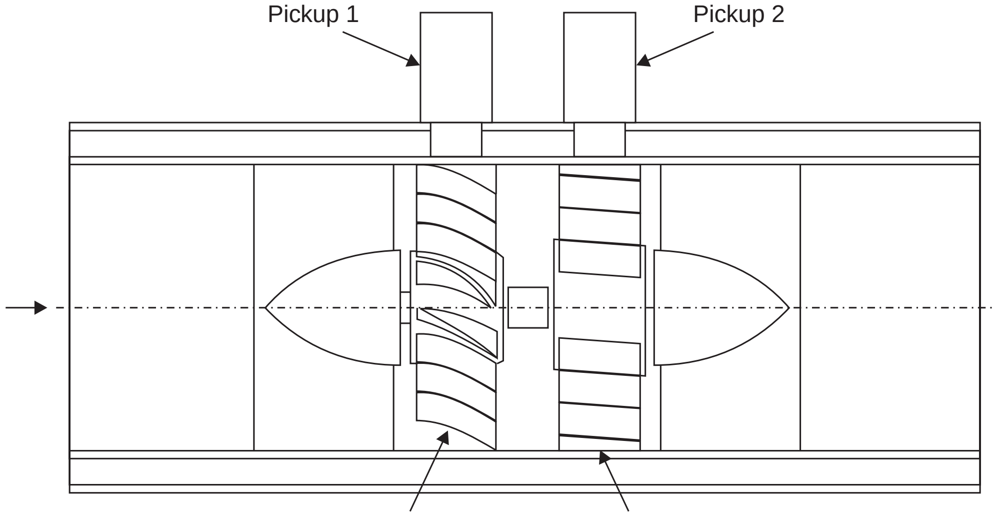



**Fig. 1.41** Twin-turbine mass flow meter

Each turbine is designed with a different blade angle ; therefore there is a tendency for the turbines to turn at different angular velocities. However, since the motion of the turbines is restricted by the coupling torsion member, the entire assembly rotates in unison at some average velocity, and an angular phase shift is developed between the two turbines. This angle is a direct function of the angular momentum of the fluid. As was previously shown, angular momentum is a function of mass flow. In the twin-turbine assembly, the turbines are not restrained by a spring, but the torsion member which holds them together twisted. Therefore, the angle developed between the two turbines is a direct function of the twist or torque exerted by the system.

This angle is measured by a unique method. As each turbine magnet passes its own pickup coil, the coil generates a pulse. The pulse from the upstream turbine is used to open an electronic gate, while the pulse from the down-stream turbine closes this gate. An oscillator is placed in the electronic circuit and the oscillations are counted while gate is opened. The number of oscillations is thus a function of the angle between the two turbines. Knowledge of the angle gives the value of torque which, in turn, is proportional to the mass flow rate.

### 1.4.11.5 Gyroscopic Mass Flow Meter

Another angular momentum mass flow meter shown in Fig. 1.42 operates on the principle of gyroscope. It consists of a pipe shaped in the form of a circle or a square. A motor introduces an oscillating vibration at a constant angular velocity 'ω' about the A axis. When the fluid passes through the loop, a precession-type moment is produced about the B axis and is measured by the deflection of the sensing element. This deflection can be shown to be directly proportional to mass flow.

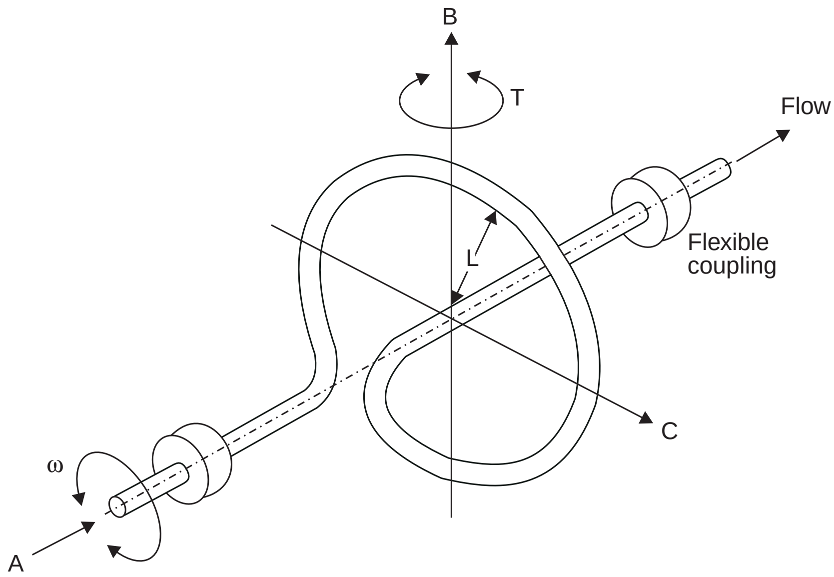



**Fig. 1.42** Gyroscopic Mass Flow meter

The gyroscopic mass flow meter can handle slurries in the medium pressure and temperature ranges but its industrial use is very limited due to its high cost and inability to handle high flow rates.

### 1.4.11.6 Coriolis Mass Flow Meter

### 1.4.11.6.1 Measuring Principle

The measuring principle is based on the controlled generation of Coriolis forces. These forces are always present when both translational and rotational movements are superimposed.

$$\vec{F}c = 2\,\Delta m\,(\vec{v}\,.\,\vec{\omega}) \qquad ...(1.46)$$

where $\vec{F}c$ = Coriolis force

$\Delta m$ = moved mass

$\vec{\omega}$ = angular velocity and

$\vec{v}$ = radial velocity in the rotating or oscillating system.

The amplitude of the Coriolis force depends on the moving mass $\Delta m$, its velocity $v$ in the system and thus on the mass flow. Instead of a constant angular velocity $\omega$, Coriolis sensor uses oscillation. In another [called promoss F $d$ $m$] sensors, two parallel measuring tubes containing flowing fluid oscillator in anti phase, acting like a tuning fork. The Coriolis forces produced at the measuring tubes cause a phase shift in the tube oscillations. This principle is illustrated in Fig. 1.43.

At zero flow, in other words when the fluid is at a standstill, the two tubes oscillate in phase (1). Mass flow causes deceleration of the oscillation at the inlet of the tubes (2) and acceleration at the outlet (3).

The phase difference (A-B) increases with increasing mass flow. Electrodynamic sensors register the tube oscillations at the inlet and outlet.

System balance is ensured by the anti phase oscillation.

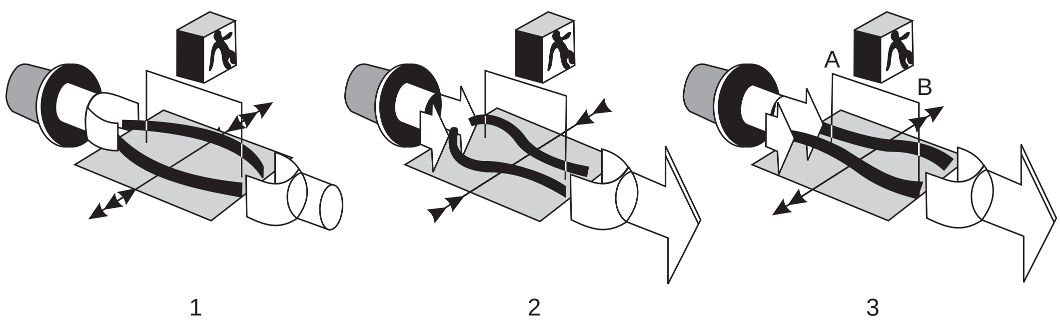



**Fig. 1.43** Coriolis principle

The classic Coriolis-type mass flow meter Fig. 1.44 consists of a centrifugal-pump impeller wheel and a vaned sensing wheel which acts as a turbine wheel to extract the angular momentum imparted to the fluid by the impeller.

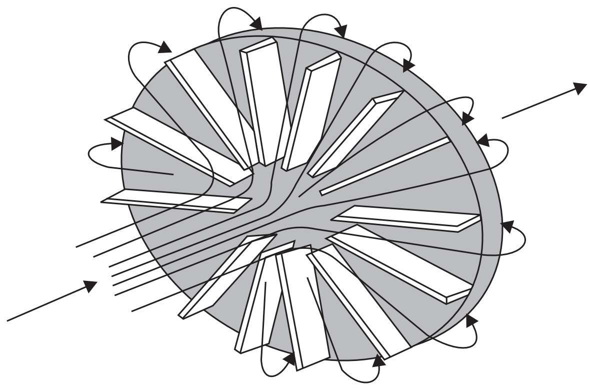


**Fig. 1.44** Classical Coriolis mass flow meter

### 1.4.11.6.2 Working

The sensing (or turbine) wheel is contained in the same housing as the impeller and is attached to the latter by a strain gauge ; the combination is driven at a constant known speed. The power applied to the impeller is merely that required to overcome the frictional drag of the system.

The torque measured is that required to impart to the fluid stream a Coriolis acceleration, and is given by the expression

$$\gamma = w\,(R_2^2 - R_1^2)\,(m/t) \qquad \text{...(1.47)}$$

where $R_2, R_1$ = outer and inner radii.

**1.4.11.6.3 Features**

1. Balanced dual-type system for universal use in a wide range of process conditions.
2. High vibration immunity.
3. Compact design, occupying very little space.
4. Measurement is independent of fluid properties.
5. Hygienic design in accordance with the latest requirement.
6. Guaranteed product quality.
7. Robust field housing (aluminium or stainless steel).
8. High accuracy.

    Liquids : ± 0.15%

    Gases : ± 0.50%.

**1.4.11.6.4 Advantages**

1. It is obstruction less.
2. It is insensitive to viscosity, pressure and temperature.
3. It can handle clean liquids, mixed fluids, multiphase fluids, foams, slurries and liquids with entrained gases.
4. This can be used for fluctuating flows.

**1.4.11.7 Thermal Mass Flow Meters**

**1.4.11.7.1 Types of Thermal Mass Flow Meters**

Thermal flow meters can be divided into two categories :

1. Flow meters that measure the rise in temperature of the fluid after a known amount of heat has been added to it. They can be called heat transfer flow meters.
2. Flow meters that measure the effect of the flowing fluid on a hot body. These instruments are sometimes called hot wire probes or heated-thermopile flow meters.

Both types of flow meters can be used to measure flow rates in terms of mass, a very desirable measurement, especially on gas service.

**1.4.11.7.2 Heat Transfer Flow Meters**

The equation of the heat transfer flow meter is based on :

$$Q = W\,C_P\,(T_2 - T_1) \qquad \text{...(1.48)}$$

where $Q$ = Heat transferred (Cal/hr)

$W$ = Mass flow rate of fluid (kg m/hr)

$C_P$ = Specific heat of fluid (Cal/kg m °C)

$T_1$ = Temperature of the fluid before heat is transformed to it (°C)

$T_2$ = Temperature of the fluid after heat has been transferred to it (°C)

Solving for W, we get

$$W = \frac{Q}{C_P (T_2 - T_1)} \quad ...(1.49)$$

A simple flow meter based upon this equation is shown schematically in Fig. 1.45.

Heat is added to the fluid stream with an electric immersion heater. The power to the heater equals the heat transferred to the fluid (Q) and is measured by a Watt meter. $T_1$ and $T_2$ are thermocouples or resistance thermometers. By measuring Q, $T_1$ and $T_2$, the flow rate (W) can be calculated as specific heat of the fluid ($C_p$) is known. $T_1$ and $T_2$ do not have to be separately detected ; they can be connected together so that the temperature difference ($T_2 - T_1$) is measured directly.

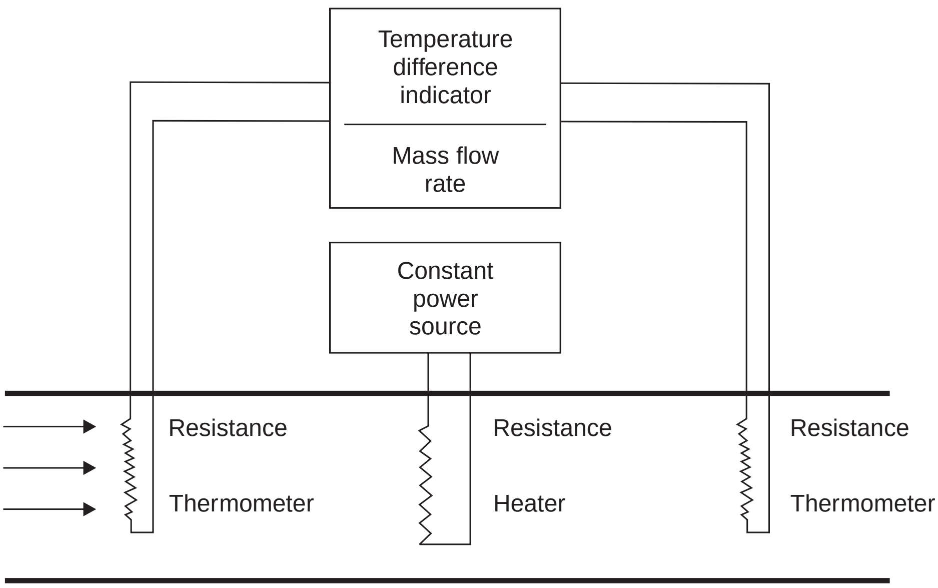



**Fig. 1.45** Heat transfer flow meter

**1.4.11.7.3 Thermal Flow Meter with External Elements and Heater**

A flow meter using heat transfer principle described above has many limitations. The temperature sensors and the heater must protrude into the fluid stream. Thus these components (particularly the heater) are easily damaged by corrosion and erosion. Furthermore, the integrity of the piping is sacrificed by the protrusions into the fluid stream, increasing the danger of leakage.

To overcome these problems, the heater and the upstream and downstream temperature sensors can be mounted outside of the piping, which is shown in Fig. 1.46.

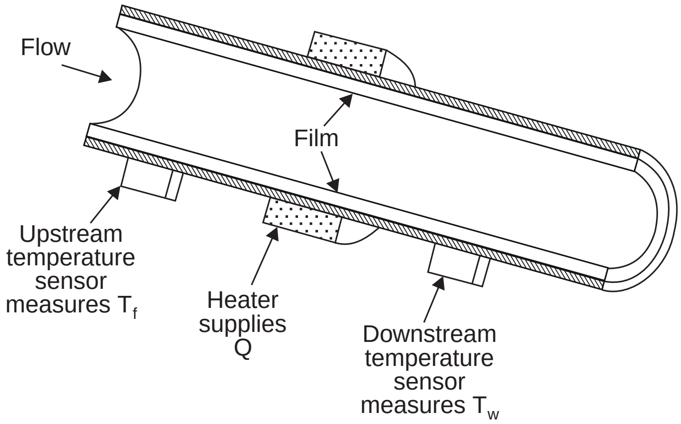



**Fig. 1.46** Thermal flow meter with external elements and heater

In this type of construction the heat transfer mechanism becomes more complicated and the relationship between mass flow and temperature difference becomes non-linear and to overcome this non-linear relationship, heated tube type is introduced.

### 1.4.11.7.4 Heated Tube-Type Mass Flow Meter

Fig. 1.47 illustrates the non-linear shift in $\Delta T$ in a heated-tube-type flow meter, where the asymmetricity of the temperature distribution increases with flow.

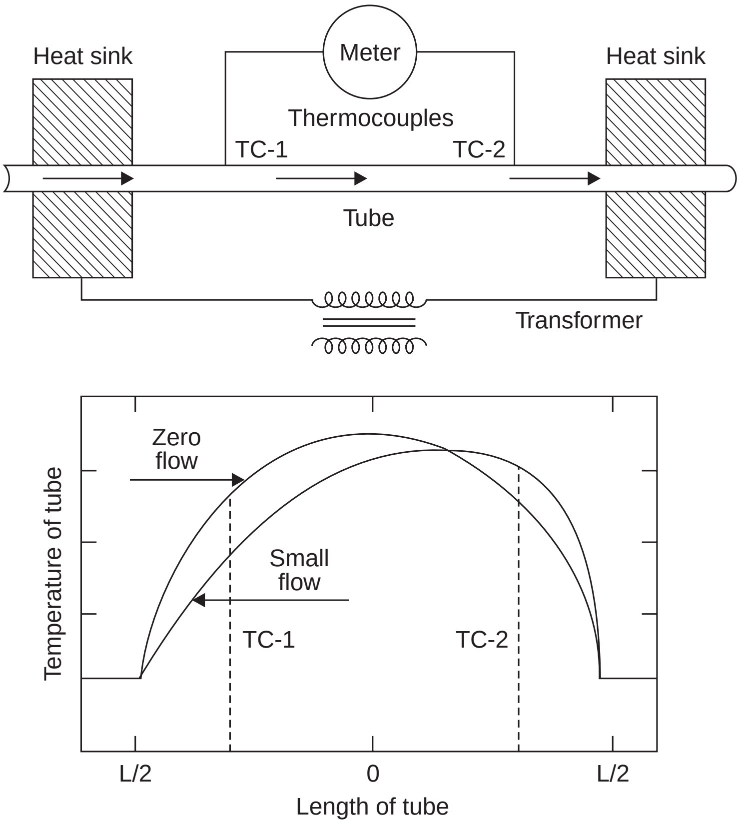



**Fig. 1.47** Heated tube-type mass flow meter

In this type of flow meter, when a fluid flows in a pipe, a thin layer (film) exists between the main body of the fluid and the pipe wall. When heat is passing through the pipe wall to the fluid, this layer resists the flow of heat. If the heater is sufficiently insulated and if the piping material is a good conductor, the heat transfer from the heater to the fluid can be expressed as

$$Q = hA\,(T_w - T_f) \qquad ...(1.50)$$

where $h$ = film heat transfer coefficient

A = Area of pipe through which heat is passing

$T_w$ = Temperature of wall

$T_f$ = Temperature of fluid.

The film heat transfer coefficient '$h$' can be defined in terms of fluid properties and tube dimensions.

These types of flow meters are best suited for the measurement of homogeneous gases and are not recommended for applications where the process fluid composition or moisture content is variable. In order for these flow meters to be useful in a system, both the thermal conductivity and the specific heat of the process fluid must be constant.

**1.4.11.7.5 By Pass-Type Designs**

In order to make the heat-transfer-type flow meter suitable for the measurement of larger flow rates, the by pass designs have been introduced which is shown in Fig. 1.48.

The thermal flow meter tubes in these bypass units are small capillary tubes, usually under 3 mm diameter. Their small size is advantageous in minimizing the electric power requirement and also in increasing their speed of response, but it necessitates the use of upstream filters to protect against plugging.

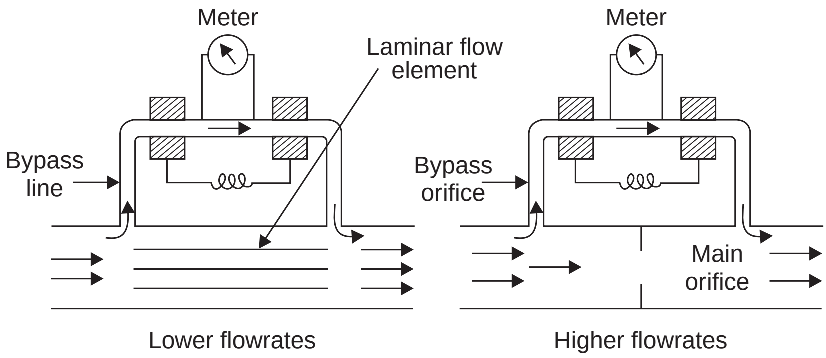



**Fig. 1.48** Bypass-type thermal mass flow meters

**1.4.11.7.6 Hot Wire probes**

In this design two thermocouples (A and B) are connected in series forming a thermopile. A schematic of this type of flow meter is shown in Fig. 1.49.

This thermopile is heated by passing an alternating current through it. A third thermocouple (C) is placed in the direct current output circuit of the thermopile. Alternating current does not pass through this thermocouple, and it is therefore not electrically heated.

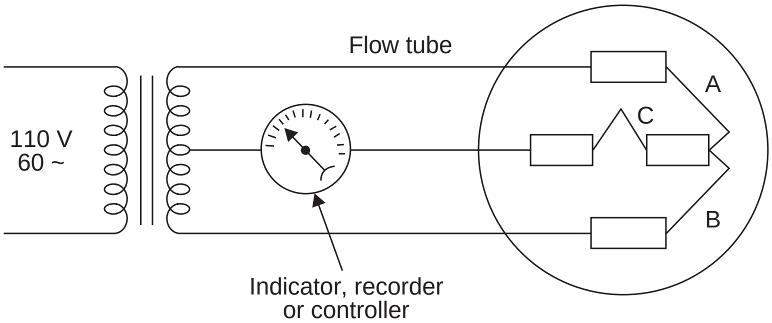



**Fig. 1.49** Hot wire flow-sensing probe

This assembly is inserted into the process fluid (usually gas) stream. The gas cools the heated thermopile by convection. Since the AC input power to the thermopile is held constant, the thermopile will attain an equilibrium temperature and produce an emf, that is a function of the gas temperature, velocity, density, specific heat and thermal conductivity. The third, unheated thermocouple (C) generates an emf that is proportional to the gas temperature. This cancels the effect of the ambient gas temperature on the output signal of the heated thermopile. A and B are the heated thermocouples ; C is the unheated one.

The output signal (voltage) of this instrument is given by the equation :

$$e = \frac{C}{2\,(\pi\, KC_P\, \rho\, dv)^{1/2} + K} \qquad ...(1.51)$$

where $e$ = Voltage generated

C = instrument constant

K = Thermal conductivity of fluid

$C_P$ = Specific heat of fluid

$d$ = diameter of heated thermocouple wire

$v$ = velocity of fluid

$\rho$ = density of the fluid.

Since K is very small, and since the term $(KC_P\, \rho)^{1/2}$ remains constant over a wide range of temperatures, this type of instrument can be used to measure the mass flow rate of gases.

#### 1.4.11.8 Volume Flowmeter Plus Density Measurement : (Radiation-Type Mass Flowmeters) :

One of the earliest methods of mass flow determination was to install two separate sensors—one to measure the volumetric flow, the other to detect the density of the flowing stream—and then use the two transmitter signals as inputs into a mass flow computing module. While feasible, the products of different suppliers and corrections for such process variables as temperature, pressure, viscosity, particle sizes and velocity profile changes. The introduction of the density/mass flow systems has made it easier to use this technique.

The key working component in these combination designs is the multiple input transmitter, as illustrated in Fig. 1.50, which in addition to a radiation–type density input also accepts a flow measurement signal from any volumetric flow meter. Based on these two inputs, the microprocessor–based transmitter generates an output signal, which relates to mass flow.

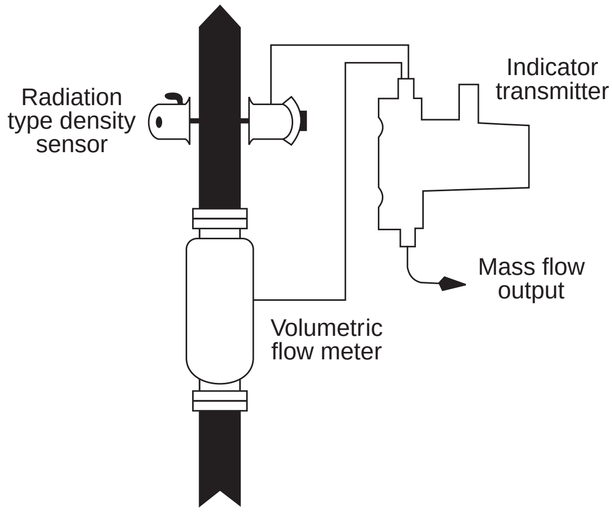



**Fig. 1.50** Combination mass flow system

A further improvement occurred in the design of these density/mass flow systems when the density and volumetric flow sensors were combined into a single package (Fig. 1.51).

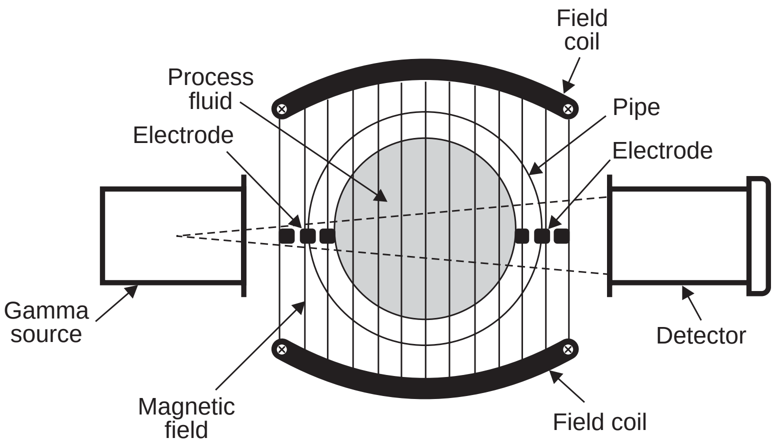



**Fig. 1.51** Mass Flow meter combining a magnetic flow meter and a radiation—type densitometer in a single unit

These units are usually comprised of a magnetic flow meter and a gamma-radiation-based densitometer, all in a single unit with a microcomputer. This mass flow unit does not require compensation for changes in process variables and is installed as a single, obstructionless mass-flow sensor. Its features and materials of construction are similar to those of a magnetic flow meter, except that it is bulkier and more expensive, due to incorporation of the radiation-type densitometer. Because the flow sensor is a magnetic flow meter, the unit is also limited to being used on process fluids having at least 3.0 μS/cm conductivity.

## 1.5 Electrical Type Flow Meter

### 1.5.1 Electromagnetic Flow Meter

#### 1.5.1.1 Principle

Electromagnetic flow meters use Faraday's law of electromagnetic induction for making a flow measurement. Faraday's law states that, whenever a conductor of length '$l$' moves with a velocity '$v$' perpendicular to a magnetic field 'B', an emf '$e$' is induced in a mutually perpendicular direction which is given by

$$e = Blv \qquad ...(1.52)$$

where B = Magnetic flux density (Wb/m$^2$)

$l$ = length of conductor (m)

$v$ = Velocity of the conductor (m/s)

The volume flow rate Q is given by

$$Q = (\pi d^2/4)\, v \qquad ...(1.53)$$

where $d$ = diameter of the pipe

$v$ = average velocity of flow (conductor velocity in this case)

From equation (1.52)

$$v = e/Bl \qquad ...(1.54)$$

$$Q = \pi d^2 e/4Bl$$

$$Q = Ke$$

where K is a meter constant.

Thus the volume flow rate is proportional to the induced emf.

In the electromagnetic meter, the constant magnetic field is generated around the pipe by magnet and the flowing liquid acts as a conductor. The flowing liquid can be regarded as a continuous series of discs passing through the magnetic field, the bore of the pipe being directly proportional to length of the conductor. Thus the emf generated is directly proportional to the velocity of flow. The complete compensation for variation in the field-strength due to voltage fluctuation can be had by using a null-balance form of measuring instrument energised from the same source as the magnet.

The flow tube of the electromagnetic type meter containing the detecting electrodes supplied as a separate unit with flanged ends which can be bolted into the main pipe into which liquid flow is to be measured. The flow tube has got the same bore as that of the pipe line into which meter is to be installed and is insulated from the liquid being metered. The flow tube bore is protected by an insulated lining of glass or neoprene which also serves to prevent the short-circuiting of emf through the electrodes. The flow tube should have high electrical resistivity so that the magnetic flux does not by-pass the metered liquid and also to minimise the eddy currents.

The electrode potential is detected by two metal electrodes essentially of the point type made of stainless steel, or platinum where high resistance to corrosion is necessary. These are located diametrically opposite to each other with their surfaces flush with the inside surface of the lining, so that they do not disturb the flow pattern.

Thus the electro magnet is of the core type and consists of two saddle shaped copper coils. This flow tube is rigidly located in the air gap and the laminated iron core, for focussing the magnetic field in a direction at right angles to the flowing liquid, being positioned beneath the coils. At alternating electric supply is used to energize electro magnet as a.c. supply avoids polarisation of the electrodes.

Thus the emf across the electrodes will be directly proportional to the velocity of flows of the metered liquid and it will not be influenced by variations in the specific resistance of the liquid if there is no current flow through it. For this purpose null balance potentiometer is used. A simplified circuit is shown in Fig. 1.52.

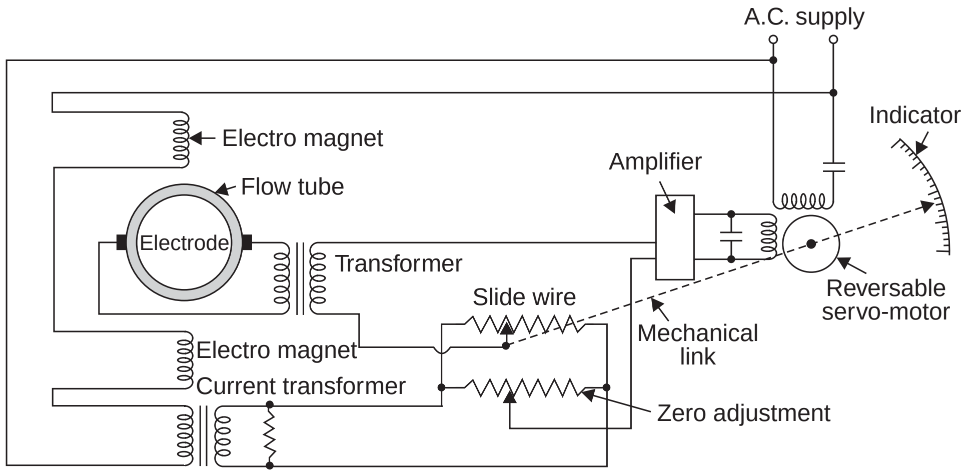



**Fig. 1.52** Electromagnetic flow meter

For obtaining perfect balance it is essential that the input and feedback signals must be equal in phase as well as in magnitude. A very small difference in phase can also cause lot of error as the input signal can be resolved into two components, one in phase with the feedback and one 90 degrees out of phase. The circuit must be designed to be insensitive to any 90 degrees out of phase signals, which appear due to the self capacity of the transmission line connected with a high source resistance. Further as the source resistance of an electromagnetic meter is both large and variable, the 90 degrees out of phase component is not stable and, therefore, automatic provision to suppress it is desirable. The movement of the slide wire contact arm is used to drive the indicating/recording instrument.

### 1.5.1.2 AC and DC Excitation Schemes

In AC type magnetic flow meters a.c. line voltage is applied to the magnetic coils. The signal generated is a low level AC signal in the high μV to low *m*V range. A more recent development is the pulsed DC type magnetic flow meter. In this design, the coils are periodically energized. There are many forms of excitation in use, but generally they can be categorized into two families : those which use on-off excitation and those which use plus-minus excitation. In either case, the principle is to take a measurement of the induced voltage when the coils are not energized and to take a second measurement when the coils are energized and the magnetic field has stabilized. Fig. 1.53 shows some of the types of excitation offered.

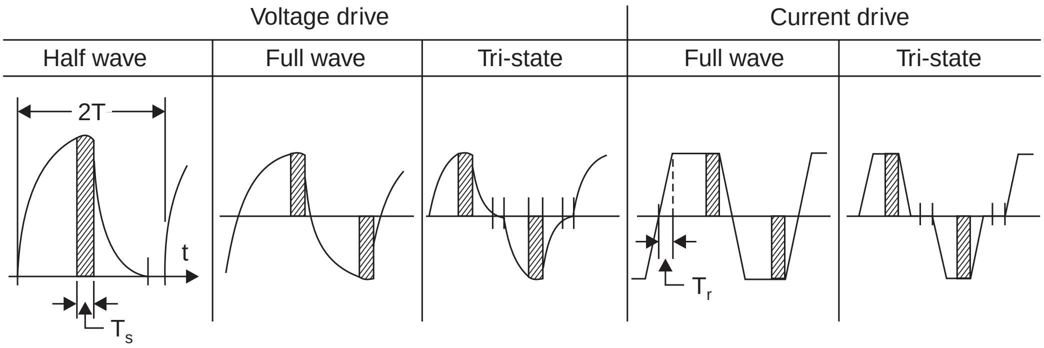



**Fig. 1.53** Types of pulsed DC Coil excitation

In all of the pulsed DC approaches, the concept is to take a measurement when the coils are excited and store (hold) the information and then take a second measurement of the induced voltage when the coils are not excited. The voltage induced when the coils are energized is a combination of both noise and signal. The induced voltage when the coils are not energized is noise only. Subtracting the noise measurement from the signal plus noise yields signal only which is illustrated in Fig. 1.54.

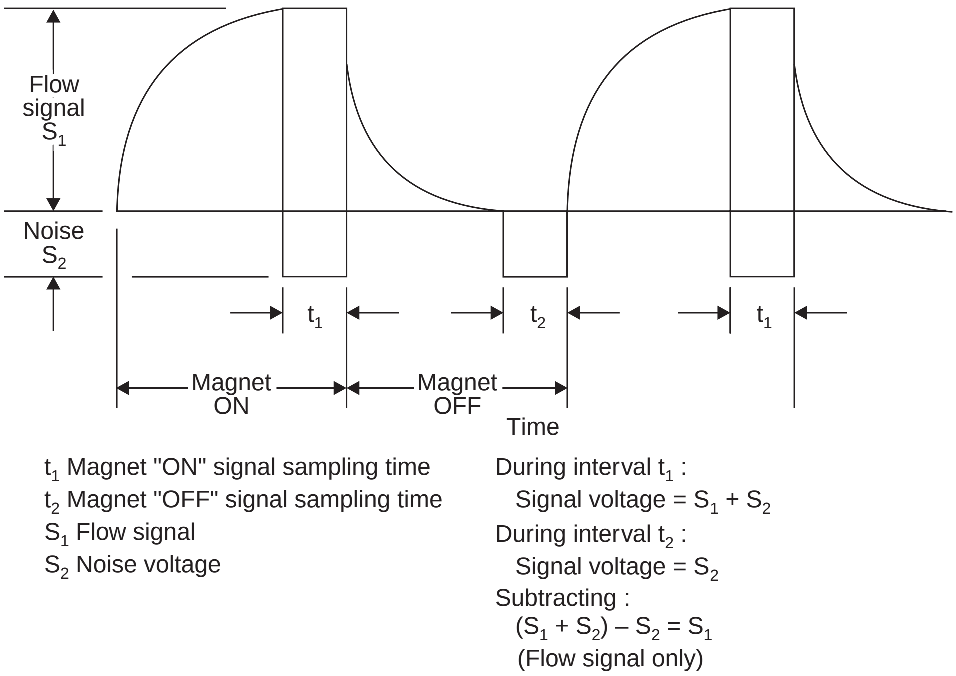



**Fig. 1.54** Plot of the output signal

The pulsed DC-type systems establish zero during each on-off cycle. This occurs several times every second. Because zero is known, the end result is that pulsed DC systems are potential percent-of-rate systems.

The AC type systems must be periodically re-zeroed by stopping flow and maintaining a full pipe in order to zero out any voltage present at that time. The noise voltage can change with time, resulting in a potential offset. Therefore AC-type systems normally are percent-of-full scale systems.

### 1.5.1.3 Dual-Frequency Excitation

Changing the method of excitation from line frequency (AC) to low frequency (DC) provided dramatic improvements in both the accuracy and the zero stability of electromagnetic flow meters. A limitation of low frequency (DC) designs is their relatively low speed of response (0.2—2 sec) and their sensitivity to measurement noise caused by slurries or low conductivity fluids.

The idea behind dual-frequency excitation is to apply both and thereby benefit from both of their advantages : The zero stability of low-frequency excitation and the good noise rejection and high speed of response of high-frequency excitation. This is achieved by exciting the magnetic field coils by a current with such a compound waveform as illustrated in Fig. 1.55. One component is a low-frequency waveform, much below 50 Hz, which guarantees good zero stability. The output generated by the low-frequency signal is integrated via a long time constant to provide a smooth and stable flow signal.

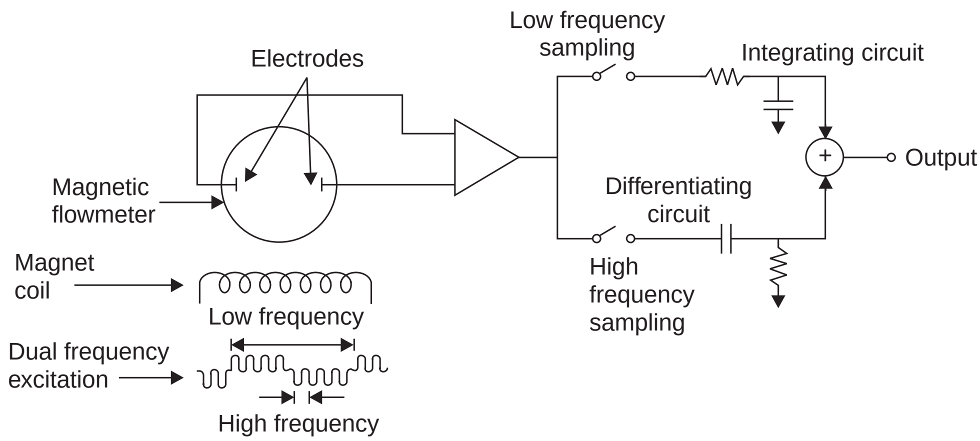



**Fig. 1.55** Dual-frequency excitation Design

The high-frequency component is superimposed on the low-frequency signal to provide immunity to noise caused by low conductivity, viscosity, slurries or electrochemical reactions. The output generated by a high-frequency component is sampled at a high frequency and is processed in a differentiating circuit having the same time constant as the integrating circuit. By adding the two signals, the result is an output that is free of 'Slurry' noise and has good zero stability plus good speed of response.

### 1.5.1.4 Construction of Electromagnetic Flow Meter

Fig. 1.56 is a cutaway view showing how the principle of electromagnetic induction is employed in a practical flow meter. The basic elements of the flow meter are a section of non conducting pipe section such as glass-reinforced polyester or a nonmagnetic pipe section lined with an appropriate electrical conductor such as Teflon, Kynar, Fiberglass, Vitreous enamel, rubber, neoprene or polyurethane., among others. On alternate sides of the pipe section are magnet coils which produce the magnetic field perpendicular to the flow of liquid through the pipe. Mounted in the pipe, but insulated from it and in contact with the liquid, is a pair of electrodes which are located at right angles both to the magnetic field and the axis of the pipe.

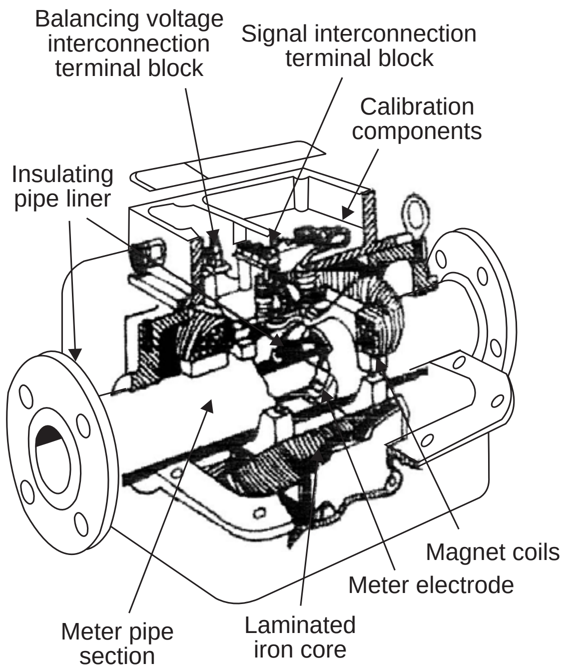



**Fig. 1.56** Cutaway view of Electromagnetic flow meter

As the liquid passes through the pipe section, it also passes through the magnetic field setup by the magnet coils inducing a voltage in the liquid ; the amplitude of the voltage is directly proportional to the liquid velocity. This voltage is conducted by the electrodes to a separate converter which in effect is a precision voltmeter capable of accurately measuring the voltage generated and converting that voltage to the desired control signals. These may be equivalent electronic analog signals, typically (4-20) mA DC, or a frequency or scaled pulse output.

### 1.5.1.5 Limitations of electromagnetic Flow Meters

(*i*) The substance being measured must be conductive. Therefore, it can't be employed for metering the flow rate of gases and steam, petroleum products and similar liquids having very low conductivity.

(*ii*) To render the meter insensitive to variations in the resistance of liquid, the effective resistance of the liquid between the electrodes should not exceed 1% of the impedance of the external circuit.

(*iii*) It is a very expensive device.

(*iv*) As the meter always measures the volume rate, the volume of any suspended matter in the liquid will be included.

(*v*) To avoid any trouble which would be caused by entrained air, when the flow tube is installed in a horizontal pipe-line, the electrodes should be on the horizontal diameter.

(*vi*) As a zero check on the installation can be performed only by stopping the flow, isolating valves are required and a bypass may also be necessary through which the flow may be directed during a zero check.

(*vii*) The pipe must run full, in case regulating valves are installed upstream of the meter.

#### 1.5.1.6 Advantages of Electromagnetic Flow Meter

(*i*) The obstruction to the flow is almost nil and therefore this type of meters can be used for measuring heavy suspensions, including mud, sewage and wood pulp.

(*ii*) There is no pressure head loss in this type of flow meter other than that of the length of straight pipe which the meter occupies.

(*iii*) They are not very much affected by upstream flow disturbances.

(*iv*) They are practically unaffected by variation in density, viscosity, pressure and temperature.

(*v*) Electric power requirements can be low (15 or 20 W), particularly with pulsed DC-types.

(*vi*) These meters can be used as bidirectional meters.

(*vii*) The meters are suitable for most acids, bases, water and aqueous solutions because the lining materials selected are not only good electrical insulators but also are corrosion-resistant.

(*viii*) The meters are widely used for slurry services not only because they are obstruction less but also because some of the liners such as polyurethane, neoprene and rubber have good abrasion or erosion resistance.

(*ix*) They are capable of handling extremely low flows.

#### 1.5.1.7 Disadvantages of EM Flow Meter

(*i*) These meters can be used only for fluids which have reasonable electrical conductivity.

(*ii*) Accuracy is only in the range of ± 1% over a flow rate range of 5%.

(*iii*) The size and cost of the field coils and circuitry do not increase in proportion to their size of pipe bore. Consequently small size meters are bulky and expensive.

#### 1.5.1.8 Applications of EM Flow Meters

This electromagnetic flow meter being non intrusive type, can be used in general for any fluid which is having a reasonable electrical conductivity above 10 microsiemens/cm. Fluids like sand water slurry, coal powder, slurry, sewage, wood pulp, chemicals, water other than distilled water in large pipe lines, hot fluids, high viscous fluids specially in food processing industries, cryogenic fluids can be metered by the electromagnetic flow meter.

### 1.5.2 Ultrasonic Flow Meters

#### 1.5.2.1 Introduction

Pressure variations travel through a fluid at the velocity of sound relative to the fluid. If fluid is in motion with certain velocity, then the absolute velocity of pressure disturbance propagation is the algebraic sum of the two. The term 'ultrasonic' refers to the pressure differences (usually are short bursts of sine waves) whose frequency is above the range audible to human hearing which is 20 to 20000 Hz.

**1.5.2.2. Principle**

The ultrasonic flow meter operates on the principle that the velocity of sound in a fluid in motion is the resultant of the velocity of sound in the fluid at rest plus or minus the velocity of the fluid itself.

**1.5.2.3 Types of Ultrasonic Flow Meters**

(*i*) Transit time flow meters

(*ii*) Doppler Flow meter.

**1.5.2.3.1 Transit Time Flow Meters**

As the name implies, these devices measure flow by measuring the time taken for an ultrasonic energy pulse to traverse a pipe section, both with and against the flow of the liquid within the pipe. Fig. 1.57 shows a representative transit time flow meter.

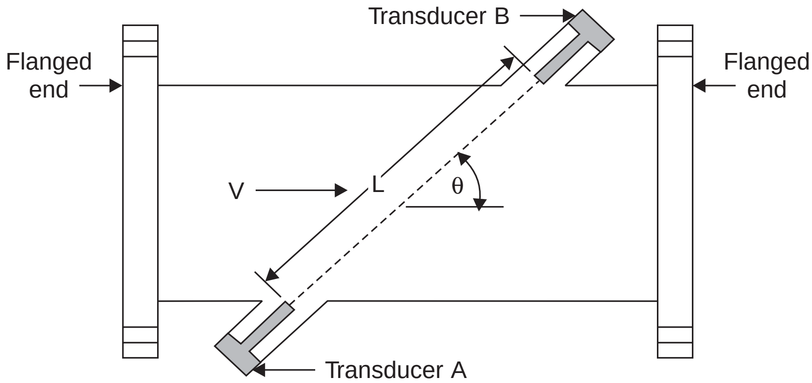



**Fig. 1.57** Transit-time flow meter

The time ($t_{AB}$) for the ultrasonic energy to go from transducer A to transducer B is given by the expression :

$$t_{AB} = L/(C + V. \cos \theta) \quad ...(1.56)$$

The time ($t_{BA}$) to go from B to A is given by

$$t_{BA} = L/(C - V.\cos \theta) \quad ...(1.57)$$

where C is the speed of sound in the fluid

L is the acoustic path length in the fluid

and θ is the angle of the path with respect to the pipe axis.

By combining and simplifying, it can be shown that for V << C :

$$\Delta t = t_{BA} - t_{AB} = 2.L.V. \cos \theta/C^2 \quad ...(1.58)$$

It can be shown that :

$$V = L.\Delta t/2 \cos \theta\, t_A^2 = K\, \Delta t/t_A^2 \quad ...(1.59)$$

where $t_A$ is the average transit time between the transducers.

Since the cross sectional area of the pipe section or 'spool pipe' is known, the product of area and velocity will yield the volumetric flow rate.

**1.5.2.3.2 Frequency Difference-Type**

In this type, the reciprocals of transit times are used. This leads to a frequency difference ($\Delta f$) which is proportional to the flow velocity V. The difference in frequencies is related to the velocity as follows :

$$V = \Delta f.L/2.\cos\theta \qquad ...(1.60)$$

The multipulse time shift reflection method uses one or more pulses and times them to determine the change in range per second to an ensemble of scatters. The change in range per unit time yields the velocity of scatters.

**1.5.2.4. Flow Meter Construction**

The ultrasonic flow meter usually consists of an electronic housing, transducers and a pipe section. A spool piece with integral transducer is one of the most common types of construction and it is shown in Fig. 1.57. The manufacturer mounts the transducers to a flanged pipe section (spool piece). Usually the unit is calibrated by the manufacturer to meet the user's specifications. The spool piece thus becomes an integral part of the hydraulic system so it is not easily retrofitted into an existing system.

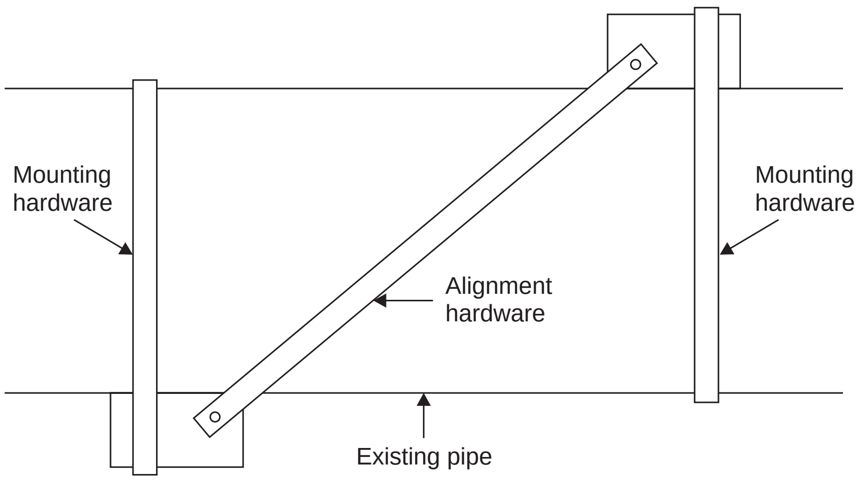



**Fig. 1.58** External Transducers

Clamp-on transducers are capable of being mounted outside an existing pipe as shown in Fig. 1.58. This type of system can be calibrated by the manufacturer only if detailed information on pipe diameter, pipe wall thickness, process fluid, percent of solids concentration, process temperature, variations in process temperature etc. are also provided by the customers. This type of flow meter is easily retrofitted onto an existing system, since no pipe section needs be installed.

## 1.5.2.5 Performance

As with most flow meters, the spool piece or pipe section must always be full to assure proper operation and volumetric flow indication. Most manufacturers will specify the minimum distance from valves, pumps, etc. that will ensure accurate flow meter performance. Typically 10 to 20 diameters upstream and 5 diameters downstream are required. The flow meter relies upon an ultrasonic signal traversing across the pipe ; therefore, the liquid must be relatively free of solids and air bubbles. Bubbles in the flow stream generally cause more attenuation than solids and so the flow meter can tolerate a large percentage of solids than bubbles.

Depending on the process fluid, proper transducer materials and protection must be chosen to prevent transducer damage due to chemical action. Process temperature limitations must also be considered for proper flow meter application.

Accuracy for a simple path flow meter is around 1 to 2% of rate depending upon design, velocity, pipe size and process. Repeatability is typically about 0.5% depending upon velocity range and calibration.

To improve performance and accuracy for larger pipe sizes, some suppliers offer flow meters with two, four or more pairs of transducers arranged to interrogate multiple acoustic paths. The cost of such units is higher than that of a single path flow meter.

**1.5.2.6 Doppler Flow Meters**

This type of flow meter is based on Doppler principle. The transmitter of a Doppler flow meter projects an ultrasonic beam at a frequency of about 0.5 MHz into the flowing stream and deflects the reflected frequency. The difference between transmitted and reflected velocities is called the 'beat frequency' and is related to the velocity of the reflecting surfaces (solid particles and gas bubbles) in the process stream.

**1.5.2.6.1 Principle of Operation**

As shown in Fig. 1.59, an ultrasonic wave is projected at an angle through the pipe wall into the liquid by a transmitting crystal in a transducer mounted outside the pipe. Part of the energy is reflected by bubbles or particles in the liquid and is returned through the pipe wall to a receiving crystal. If the reflectors are travelling at the fluid velocity, the frequency of the reflected wave is shifted according to the Doppler principle, in proportion to the flow velocity.

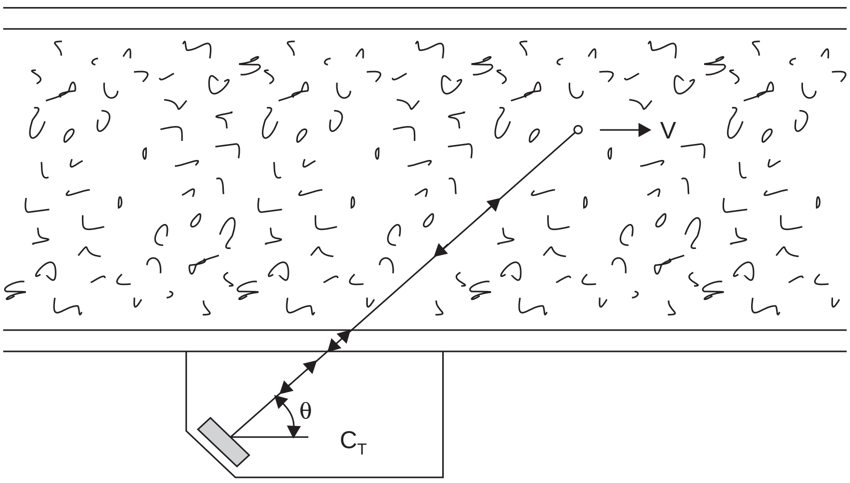



**Fig. 1.59** Doppler Flow meter Principle of operation

Combining Snell's law and Doppler equation, the flow velocity can be determined as follows if V << C.

$$V = \Delta f . C_t / (2 . f_o \, . \cos \theta) = \Delta f . K \qquad ...(1.61)$$

where $\Delta f$ = Difference between transmitted and received frequency.

$f_o$ = frequency of transmission

$\theta$ = angle of the transmitter and receiver crystal with respect to the pipe axis

$C_t$ = Velocity of sound in the transducer.

As shown in equation (1.61), velocity is a linear function of $\Delta f$. Since the inside diameter (ID) of the pipe is known, volumetric flow rate can be measured as a function of V and square of ID

$$\text{Volumetric flow rate (Q)} \propto V.(ID)^2 \qquad ...(1.62)$$

**1.5.2.6.2 Construction**

In the single transducer design, both the transmitter and receiver crystals are contained in a single transducer assembly which is to be mounted on the pipeline. Alignment of the crystal is thus controlled by the manufacturer. This approach is shown in Fig. 1.59.

In dual transducer design, the transmitter crystal and the receiver crystal are mounted separately on opposite sides of the outside of the pipe. Alignment is maintained by a mounting assembly that maintains the relative positions of the transducers as shown in Fig. 1.60.

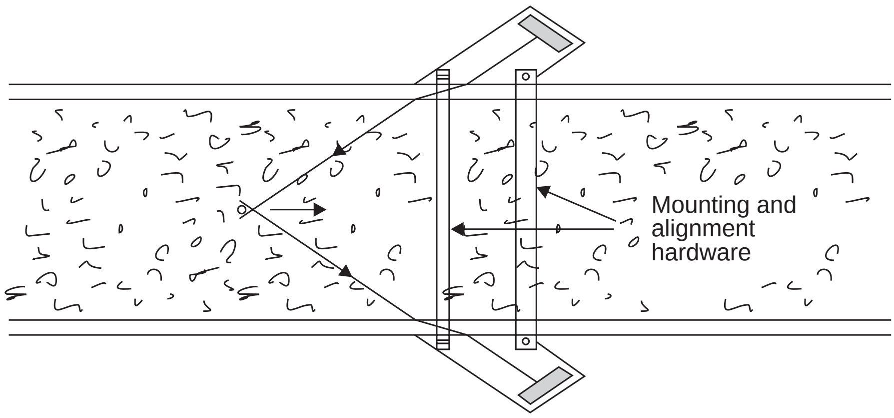



**Fig. 1.60** Two-transducer approach

When the process stream contains large amount of solids and the velocity of the solid particles near the wall is likely to be less than the average in a single transducer installation (causing large errors), it is recommended that the two-transducers approach is used. With this approach the reflected ultrasonic radiation is received from portions of the flow stream.

**1.5.2.6.3 Application and Performance**

A Doppler unit will indicate velocity in a partially full pipe as long as the transducer is mounted below the liquid in the pipe.

The minimum pipe distance required from valves, pumps etc. is typically 10 to 20 diameters upstream and 5 diameters downstream for clean fluids. This requirement can increase with process solids concentration or solids composition.

A Doppler flow meter relies upon reflectors in the flow stream to reflect ultrasonic energy. There is a lower limit for the concentration and size of solids or bubbles in the liquid that will give reliable, accurate operation. The flow must be fast enough to keep the solids or bubbles in suspension.

The Doppler flow meters will operate independently of pipe material provided the pipe is sonically conductive. Such pipes as concrete, clay and very porus cast iron absorb the ultrasonic energy and are not suited for Doppler-type flow metering.

The maximum operating temperatures is about 100°C. The inaccuracy or error of the Doppler type flow meter is about 3% of span. The error does vary with flow velocity, pipe size and flow meter calibration. Repeatability is about 1% of full span.

### 1.5.3 Laser Doppler Anemometer Systems

Anemometers are used to measure air and gas flows in a variety of applications.

#### 1.5.3.1 Principle of Operation

When sound or light is beamed into the atmosphere, the inhomogeneities in the air will reflect these beams. The resulting Doppler shift in the returning frequencies can be interpreted as an indication of wind velocity.

#### 1.5.3.2 Working

When laser-based Doppler anemometers are used, the intensity of the light scattered by the particles in the air is a function of their refractive index and the size of the reflecting particles.

The Laser Doppler anemometer (LDA) is based on the Doppler effect. The Doppler shift of frequency occurs as light is dispersed on the surface of moving particles. The shift in the frequency of the light source (laser beam) is proportional to the velocity of the particles. The frequency shift is very small (from 1 KHz upto a tenth of a MHz) in comparison with the light frequency and thus it can be directly measured. Therefore, the arrangement using the interference of the original and refracted lights is used. This is called as 'differential mode' of LDA. Fig. 1.61 illustrates the LDA Principle.

The frequency '$f$' of electrical signals produced by a particle moving with velocity 'V' is given by

$$f = \frac{2V \sin \theta / 2}{\lambda} = \left[\frac{2 \sin \theta / 2}{\lambda}\right] V$$

$$\mathbf{f = KV}$$

where $\lambda$ = Laser wavelength and $\theta$ = angle of the beam.

Beams from the laser source intersect each other in the measurement zone, where a set of interference plates are formed. When particles pass through these, they generate optical signals with flash frequencies which equal the Doppler frequency. This signal is scanned by the photo multiplier and is analysed. The signal has several cycles, variable amplitude, and high frequency and background noise.

#### 1.5.3.3 Applications

The use of this non contact measurement method is suitable for nearly all hydro dynamical and aero dynamical velocity measurement applications.

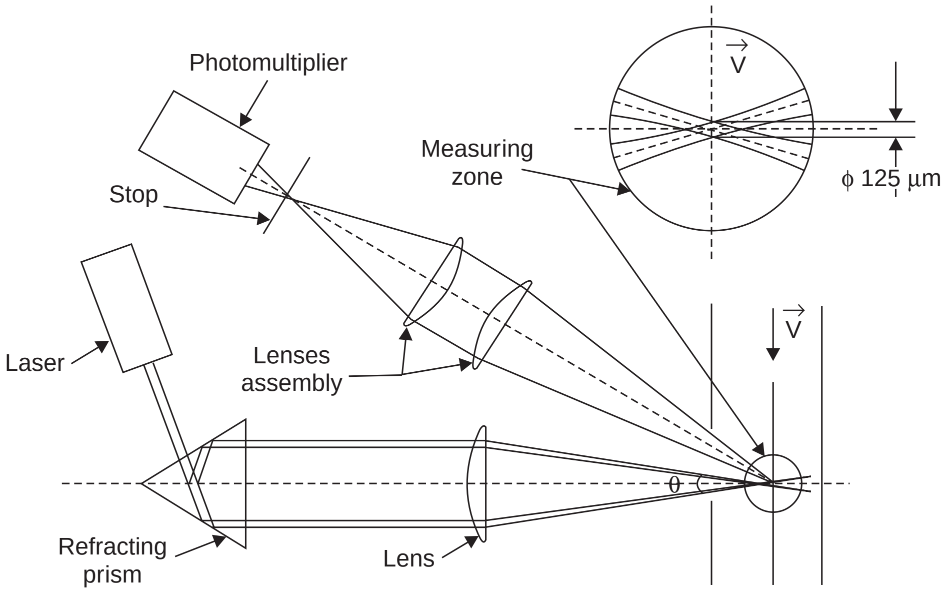



**Fig. 1.61** Operation of the laser Doppler anemometer

## 1.6 Other Types of Flow Meters

Purge flow regulators for low flow rate measurements, Cross-correlation flow meters for solids flow measurements, Belt type feeders for solids flow measurements, Vortex flow meters for moderate flow measurements and different designs of flow switches are discussed in this section.

### 1.6.1 Purge Flow Regulators

#### 1.6.1.1 Introduction

Purge flows are low flow rates of either gases or liquids. They usually serve to protect pressure taps from contacting hot or corrosive process fluids or from plugging. They can also protect electrical devices from becoming ignition sources by maintaining a positive inert gas pressure inside their housings or to protect the cleanliness of the optics of analyzers through purging.

The low flow rates of the purge media can be detected by a variety of devices including capillary, miniature orifice, metering pump, positive displacement, thermal and variable—area type sensors.

#### 1.6.1.2 Rotameter Type Purge Meter

Rotameter-type purge meter is the least expensive and most widely used purge meter. These meters take many forms, all of which are inexpensive, and are intended for low flow measurement. Most purge meters are selected to handle inert gases or liquids at low flow rates where these fluids are used as a purge ; therefore, accuracy is not critical. Purge meters are available with optional needle control valves. Fig. 1.62 shows a typical purge-type rotameter with integral needle control valve.

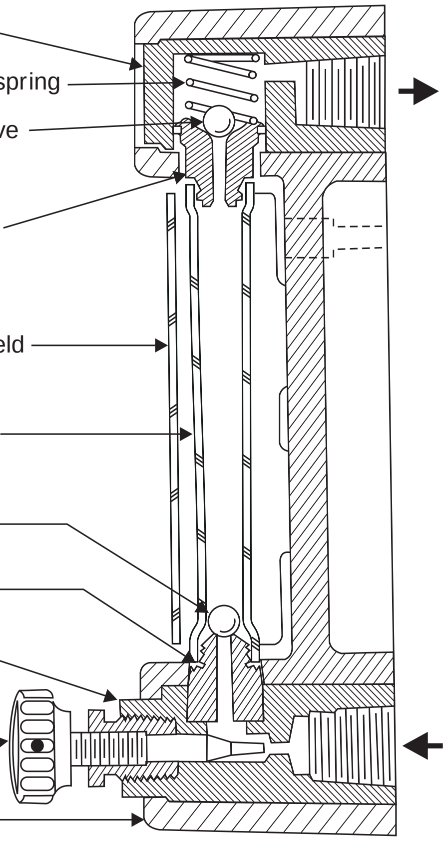



**Fig. 1.62** Purge rotameter with integral needle control valve

The metering needle valves are usually multiple-turn units provided with long stems. The opening around their needle-shaped plugs can approach capillary dimensions. The flow rate through these devices is a function of not only the opening of the valve and the pressure differential across it, but also of both the density and the viscosity of the purge media.

When the purge flow meter is combined with a differential pressure regulator, it becomes a self-contained flow controller which is illustrated in Fig. 1.63.

By adjusting springs #1 and #2 for a constant pressure difference of about 1.5 to 2 m of water, this constant pressure drop ($P_i - P_0$) is maintained across the flow control valve (V) and the purge flow is thereby fixed. Fig. 1.63 describes a configuration in which the outlet pressure ($P_0$) is constant and the inlet pressure $P_i$ is variable. Units are also available for bubbler and purge applications where the inlet pressure $P_i$ is constant and the outlet $P_0$ is variable. In that case the constant pressure drop across the valve (V) is maintained to equal ($P_i - P_0$).

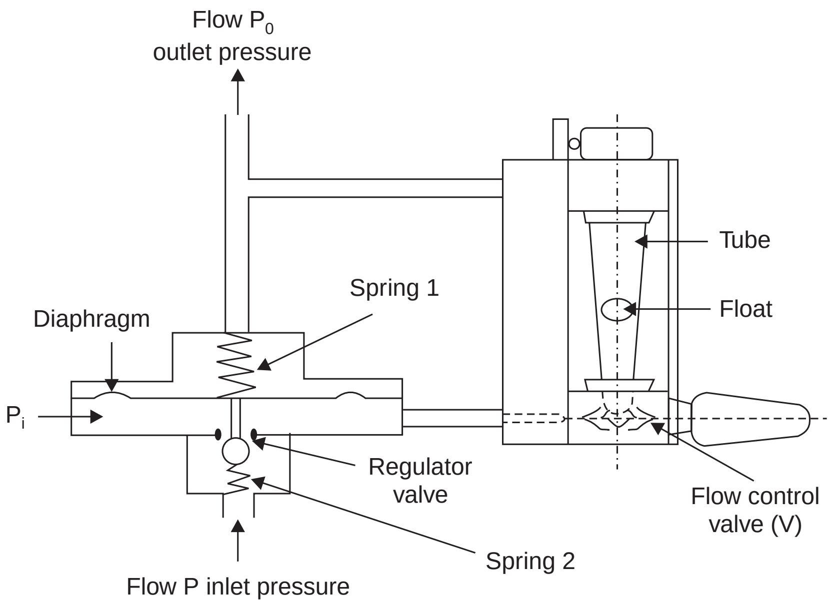



**Fig. 1.63** Purge flow regulator consisting of a glass tube rotameter, and inlet needle valve, and a differential pressure regulator

#### 1.6.1.3 Applications

Purge flow controllers on gas service are usually provided with an accuracy of 5% full scale over a range of 10 : 1.

### 1.6.2 Cross Correlation Flow Meter

#### 1.6.2.1 Introduction

The oldest and simplest methods of flow measurement are the various tagging techniquies. Here a portion of the flow stream is tagged at some upstream point and the flow rate is determined as a measurement of transmit time. Variation of this technique include particle tracking, pulse tracking, dye or chemical tracing, including the radioactive types.

#### 1.6.2.2 Working Principle

Flow metering based on correlation techniques is similar in concept to the tagging or tracing techniques because it also detects transit time. As illustrated in Fig. 1.64, any measurable process variable which is noisy can be used to build a correlating flow meter. The only requirement is that the noisy pattern must persist long enough to be seen by both detectors 'A' and 'B' as the flowing stream travels down the pipe. Flow velocity is obtained by dividing the distance between the identical pair of detectors by the transit time.

The following process variables display persistent-enough noise patterns or fluctuations so that cross-correlation flow meters can be built by using an identical pair of these sensors : Density, Pressure, Temperature, Ultrasonics, Gamma radiation, Capacitive density and Conductivity. Several of the above process variables such as temperature, gamma radiation and capacitive density have been investigated as potential sensors for correlation flow meters.

One instrument has been developed utilizing the principle of ultrasonics cross-correlation to measure heavy water flow. Others are available for paper pulp application using photometric sensors and for solids flow measurements utilizing capacitance detectors.

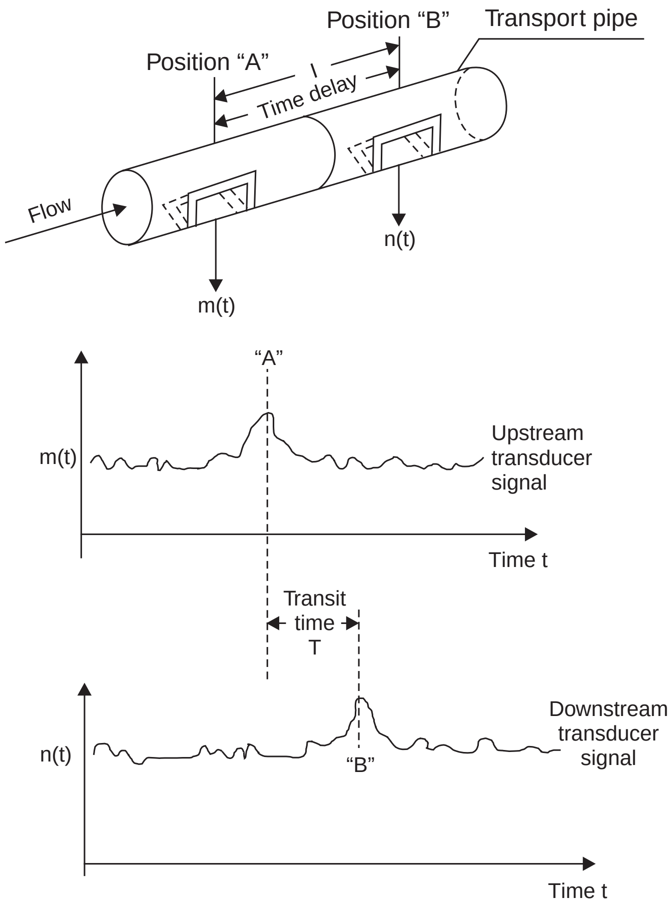



**Fig. 1.64** Cross-correlation flow metering

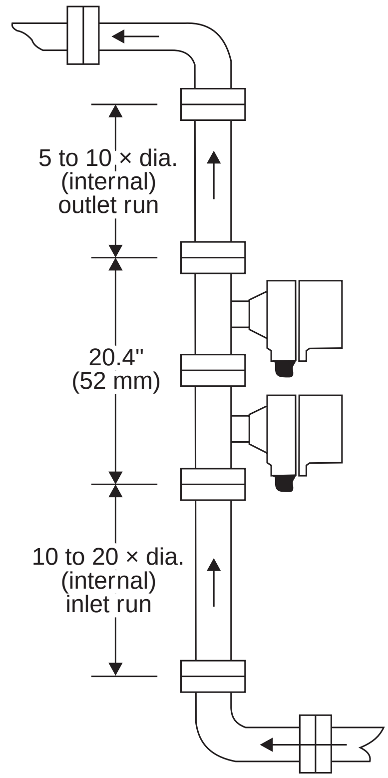



**Fig. 1.65** Installation requirements of cross-correlation type solids flow meter

Fig. 1.65 shows installation requirements of cross-correlation type solids flow meter. When fully developed, correlation flow metering can extend the ability to measure the flow not only into the most hostile process environments, but also into areas of multiphase flow.

### 1.6.2.3 Advantages

The advantages of tagging techniques include the ability to measure the velocity of only one component in a multi component flow stream without requiring calibration.

### 1.6.2.4 Applications

The applications of the cross-correlation flow meter include pumped paper pulp, pneumatically conveyed coal dust, cement, grain, plastic granules, chalk and chemical food stuffs.

## 1.6.3 Solids Flow Measurement

### 1.6.3.1 Introduction

Continuous determination of flow rate of dry materials such as coal, cement, powdered chemicals, paper and fruits is necessary in many industrial processes. Meters for measuring flow of dry materials are essentially of the weighing type, in that they determine the weight of material passing a given point.

Belt feeders are compact factory—assembled devices utilizing belts to transport the material across a weight-sensing mechanism. In the case of meters, an uncontrolled solids flow passes across a constant speed belt and the belt load signal is thus a function of gravimetric flow rate.

The feeder in its most basic form consists of a meter to which a controller and volumetric solids flow regulator is added. The flow regulator is normally a simple gate, but may be in the form of a rotary gate, screw or other volumetric control device capable of being fitted with a suitable actuator.

### 1.6.3.2 Belt Type Gravimetric Feeder

Fig. 1.66 illustrates a simpler feeder. It incorporates a constant speed belt coupled with a gate to modulate the solids flow rate such that belt load is balanced by an adjustable poise weight. The feeder, which is still used in some industrial applications today, is unique in its simplicity but includes number of disadvantages relative to more modern designs as follows :

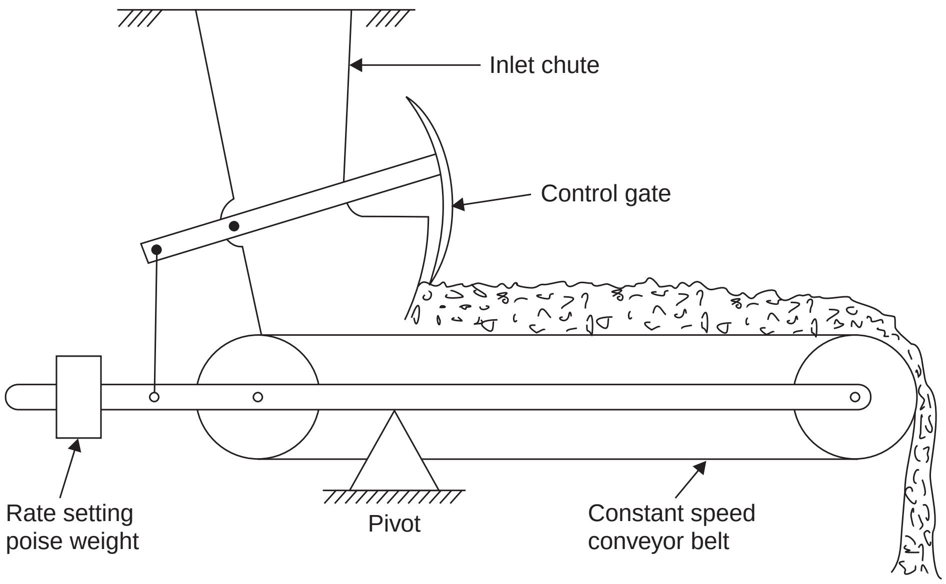



**Fig. 1.66** Early belt-type mechanical gravimetric feeder

1. The entire feeder is weighed rather than only a portion of the belt ; consequently, the low ratio of live load to tare coupled with mechanical friction in the linkage pivots results in relatively low sensitivity in the belt load detection system.

2. The position of the gate control element is proportional to the belt load error. In the same manner that a float-operated level control valve cannot maintain the level at set point if

valve supply pressure vary, this feeder cannot maintain set gravimetric rate if the bulk density of the solids varies.

It should be noted that the basic principle involving the weighing of the entire feeder has been applied in modern designs. Successful operation of these versions has been achieved by adding belt load error detecting instrumentation and by actuating the control gate from an external power source. A controller with reset function eliminates the set point error.

#### 1.6.3.3 Belt Type Electromechanical Gravimetric Feeder

Fig. 1.67 describes the basic construction of the electromechanical gravimetric feeder. Here the belt load is balanced by a mechanical beam and poise weight system which energizes one or other of two clutches via a pair of mercury switches energized by a magnet attached to the beam. These clutches actuate and establish the direction of travel of the gate-positioning

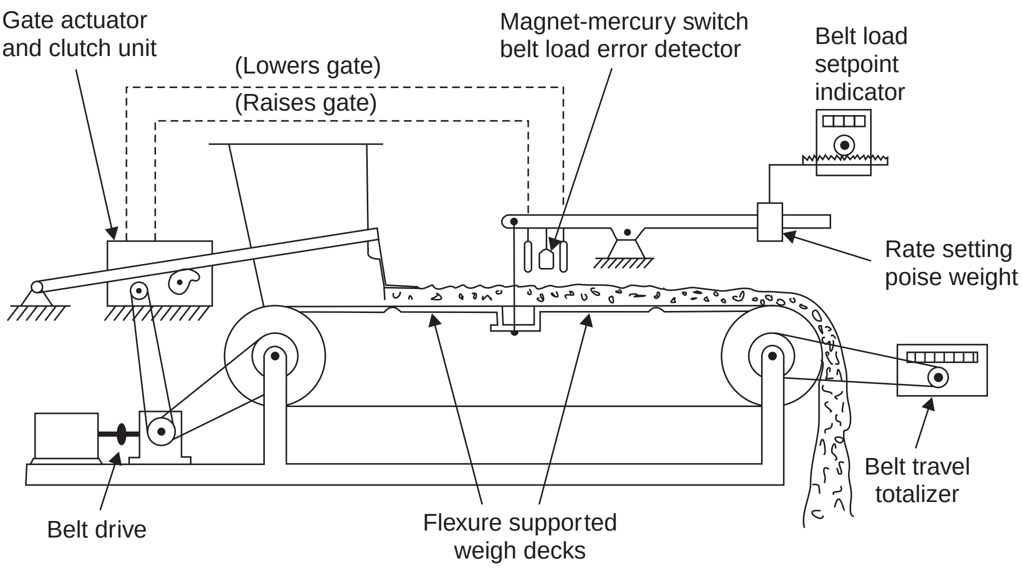



**Fig. 1.67** Belt-type electromechanical gravimetric feeder

mechanism. The gate modulates as required to maintain the desired belt load as established by the position of the poise weight on the balance beam. It can be seen that this feeder will maintain belt load regardless of changes in material density, subject to the volumetric control limits of the gate. Belt load set point is indicated by a mechanical counter geared to the beam poise weight drive. A second counter geared to the belt drive totalizes the length of the belt travelled. By varying drive gears, these counters can be provided to read directly. Total weight fed can thus be calculated by multiplying the readings of the two counters. Remote belt load set point and readout functions are available as well as a belt travel contact switch may be used to operate a remote counter or to shut down the feeder via a predetermining counter after the desired total weight of material has been fed. Adjustable micro switches actuated by gate position may be utilized to activate alarms indicating either a stoppage of the material supply to the feeder or over travel of the control gate resulting from abnormal low material density.

### 1.6.3.4 Belt Type Gravimetric Feeder with Pneumatic system

Fig. 1.68 illustrates the gravimetric meter which is available with either pneumatic or electronic weight detection and transmission system. In the case of the pneumatic version shown, the preliminary calibration procedure involves adjustment of the tare weight with the

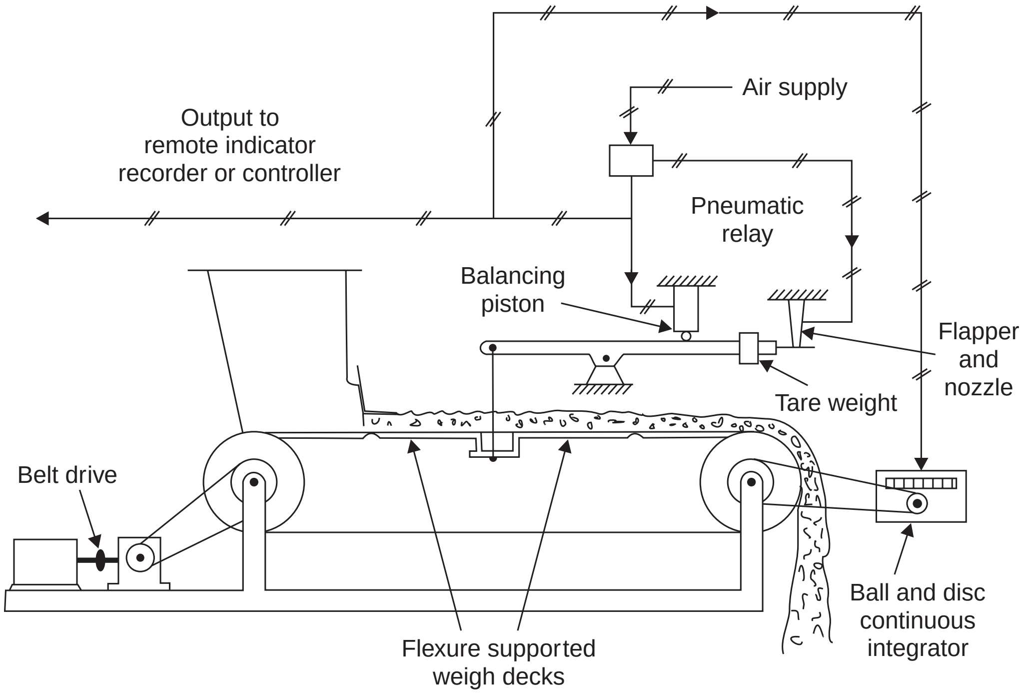



**Fig. 1.68** Belt-type gravimetric meter with pneumatic system

beam in center position, and location of the nozzle relative to the flapper. This establishes a condition such that balance is achieved when balancing piston pressure is 0.2 kg/cm$^2$. When material crosses the belt, beam movement throttles the nozzle. Nozzle back pressure is imposed on the pneumatic relay, which in turn increases its output pressure until the balancing piston rebalances the beam. The balancing pressure is thus proportional to belt load and since the belt speed is constant, balancing pressure is proportional to measured weight-rate. Also shown is an optional ball and disc integrator. The disc is driven by the front belt roll of the feeder and the ball is positioned by a pneumatic positioner. This ball and disc type integrates continuously. It is especially recommended for user with gravimetric meters in applications involving the measurement of rapidly varying instantaneous flow rates. The integrator is supplied with a digital totalizer and can be furnished with a pulse transmitting switch to operate a remote counter.

The feed rate of all belt-type gravimetric feeders is a function of the belt speed and the belt load. Belt speed is normally expressed in terms of meter per minute, while belt load is defined as kg per metre of belt.

$$\text{Feed rate} = \text{Belt speed} \times \text{Belt load}$$

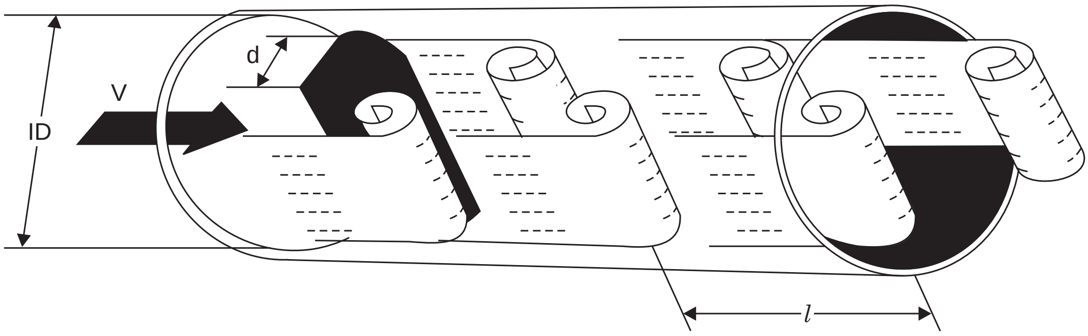
In the case of the constant speed belt feeders, rate is directly proportional to belt load. Rate set point is thus in terms of belt load, and the belt load signal generated by the device can be read out as rate.

Another method of rate adjustment utilizes belt speed variation with belt load as controlled constant. Still another involves variation of both belt speed and belt load wherein the rate signal is the multiplicand of the belt speed and belt load measurement signals generated by the feeder.

## 1.6.4 Vortex Shedding Flow Meter

### 1.6.4.1 Vortex Shedding Phenomenon

When an obstruction (a non-streamlined object) is placed in the path of a flowing stream, the fluid is unable to remain attached to the object on its downstream sides and will alternately separate (shed) from one side and then the other. The slow-moving fluid in the boundary layer on the body becomes detached on the downstream side and rolls into eddies and vortices,. Fig. 1.69. It is also noted that the distance between the shed vortices is constant, regardless of flow velocity. This principle is called as Karman's principle.




The distance between the Karman vortices (l) is only a function of the width of the obstruction (d) and therefore the number of vortices per unit of time gives flow velocity (V).

**Fig. 1.69** Karman vortices

Stated in terms of a flag fluttering in the wind, it is noted that the intervals between vortices ($l$) is constant and is only a function of the diameter of the flag pole ($d$). Therefore, the faster the wind, the faster the vortices are formed and the faster the flag flutters as a consequent, but without changing its wavelengths.

In building a flow meter based on Karman's principle, the manufacturer usually selects an obstruction width ($d$) that is one-quarter of the pipe diameter (ID). As long as the obstruction is not coated, as long as the pipe Reynold's number high enough to produce vortices and as long as the detector is sensitive enough to detect these vortices, what results is a flow meter that is sensitive to flow velocity and is insensitive to the nature of the flowing media (liquid, gas, steam), density etc.

As per Strouhal's statement, if one knows the vortex shedder width ($d$) and has a detector that is sensitive enough to count the vortices and determine the vortex frequency ($f$), one can measure the flowing velocity of any substances as :

$$\text{Flow velocity} = Kfd \quad ...(1.63)$$

where K is a constant.

**1.6.4.2 Vortex Flow Meter Detection**

As a vortex is shed from one side of the bluff body, the fluid velocity on that side increases and the pressure decreases. On the opposite side, the velocity decreases and the pressure increases, thus causing a net pressure change across the bluff body. The entire effect is then reversed as the next vortex is shed from the opposite side. Consequently, the velocity and pressure distribution adjacent to the bluff body change at the same frequency as the vortex shedding frequency.

Various detectors can be used to measure one of the following :

1. The oscillating flow across the face of the bluff body.
2. The oscillating pressure difference across the sides of the bluff body.
3. A flow through a passage drilled through the bluff body.
4. The oscillating flow or pressure at the rear of the body.
5. The presence of free vortices in the downstream to the bluff body.

A flow-sensitive detector can be either a heated thermistor element or a spherical magnetic shuttle. Detectors that are sensitive to pressure use either metal diaphragms or vanes. Pressure exerted on diaphragms can be converted into variable capacitance or variable strain or can be converted into an electrical signal through any of the sensor. Depending on the characteristics of the sensing system, the flow meter will be suitable for liquid or gas or both.

The earliest detector designs were highly sensitive to plugging and required frequent maintenance. Fig. 1.70.

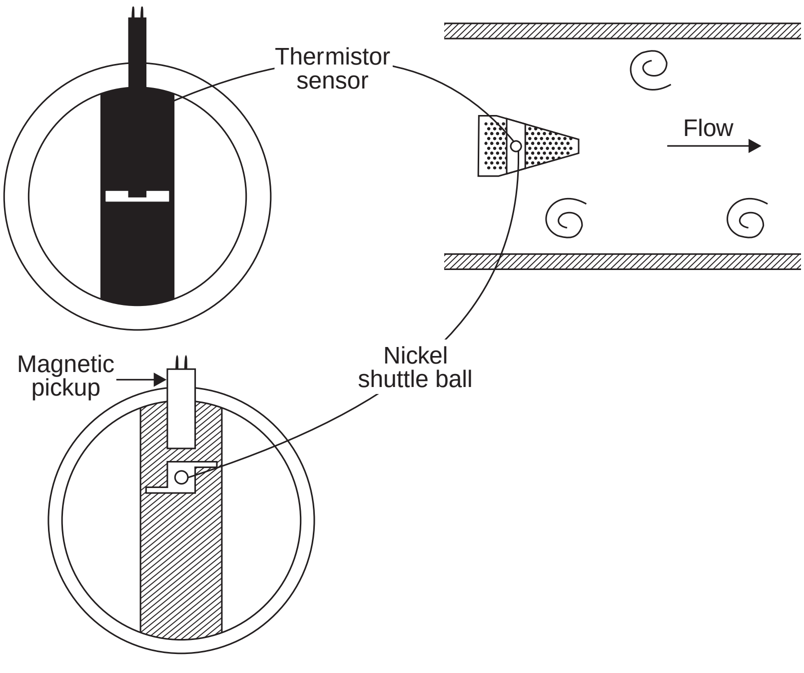



**Fig. 1.70** Early vortex flow meter detectors

Those early detectors were replaced by units that could not plug and were solid state in design. Fig. 1.71.

Other design modifications aim at compensating for background noise by using two detectors, of which one is exposed to vortex forces and the other is not, and using their difference as the measurement signal.

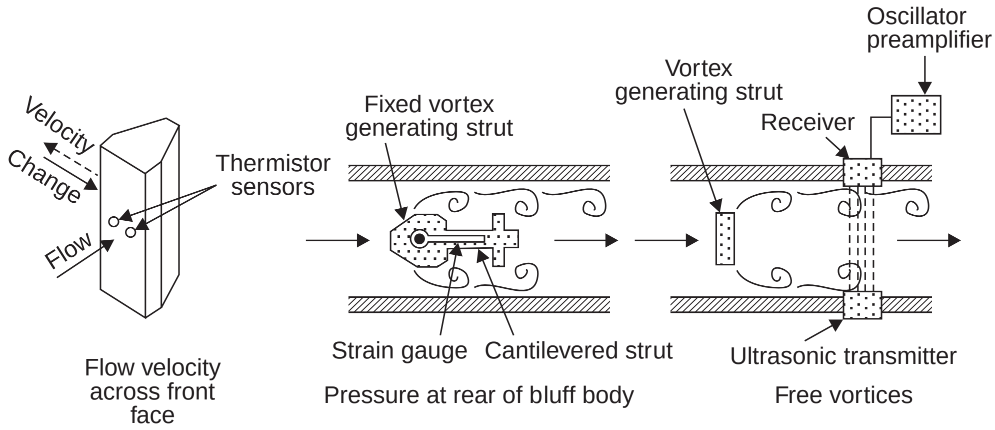



**Fig. 1.71** Solid state vortex flow meter detectors

### 1.6.4.3 Features of Vortex Shedding Flow Meter

1. The vortex shedding meter provides a linear digital output signal without the use of separate transmitters or converters, simplifying equipment installation.
2. Meter accuracy is good over a potentially wide flow range, although this range is dependent upon operating conditions.
3. The shedding frequency is a function of the dimensions of the bluff body and it ensures good long term stability of calibration and repeatability of better than ± 0.15% of rate.
4. There is no drift because this is a frequency system.
5. The meter does not have any moving or wearing components, providing improved reliability and reduced maintenance.
6. The calibration of the meter is virtually independent of the operating conditions (viscosity, density, pressure, temperature and so on) whether the meter is being used on gas or liquid.
7. The vortex shedding meter also offers a low installed cost, particularly in pipe sizes below 6 inch diameter.
8. The limitations include meter size range. Meters below 12 mm diameter are not practical.

### 1.6.4.4 Selection of Vortex Shedding Flow Meter

As the first step in the selection process the operating conditions should be compared with the meter specification. The meter wetted materials (including bonding agents) and sensors should then be checked for compatibility with the process fluid both with regard to chemical attack and safety. Applications where there are large concentrations of solids, two-phase flow, or pulsating flow should be avoided or approached with extreme caution. The meters can have a rangeability of about 20 : 1 with a pressure loss of approximately 0.2 kg/cm$^2$.

The meter's good accuracy and digital linear output signal make its application over wide flow ranges a practical proposition. The rangeability declines proportionally with increases in viscosity and decreases in density, or reductions in the maximum flow velocity of the process. Vortex shedding meters are therefore unsuitable for use of high-viscosity liquids.

## 1.6.5 Flow Switches

Flow switches are used to determine whether the flow rate is above or below a certain value. This value (set point) can be fixed or adjustable. When the set point is reached, the response can be the actuation of an electric or pneumatic circuit. When the flow switch is actuated, it will stay in that condition until the flow rate moves back from the set point by some amount. This difference between the 'set point' and the 'reactivation point' is called the switch 'differential'. The differential can be fixed or adjustable. If the differential is small, the switch is likely to cycles it control circuit as the flow actuates around its set point.

In certain applications, a manual reset feature is desirable. This will guarantee that once the switch is actuated, it will not be allowed to return to its preactuation state until manually reset by the operator. This feature is designed to require the operator to review and eliminate the cause of the abnormal flow condition before resetting the switch variations.

### 1.6.5.1 Design Variations

#### 1.6.5.1.1 Folding Paddle Switch

The least expensive and therefore the most widely used are the various paddle type devices. One such device is illustrated in Fig. 1.72. At 'no flow' the paddle hangs loosely in the pipe in which it is installed. As flow is initiated, the paddle begins to swing upward in the direction of the flow stream. This deflection of the paddle is translated into mechanical motion by a variety of techniques including a pivoting cam, a flexure type, or a bellows assembly. The mechanical motion causes the switch to open or close. If a mercury switch is used, the mechanical motion drives a magnetic sleeve into the field of a permanent magnet which trips the switch. A hermetically sealed switch will be directly actuated by the permanent magnet as it moves up or down according to the paddle movement. If a micro switch is used, the translated motion will cause direct switch actuation. The range and actuation point of paddle switches can be changed and adjusted by changing the length of the paddle. For any given pipe size, the actuation flow rate decreases as the paddle length increases.

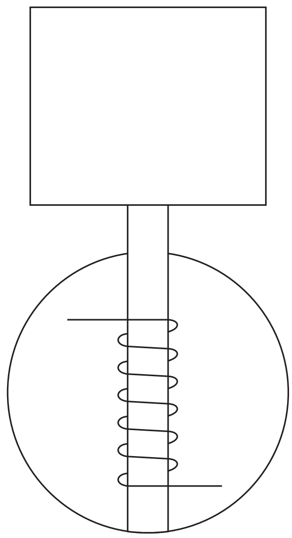


**Fig. 1.72** Folding paddle switch

Paddle-type flow switches are sensitive to pipeline turbulence, pipeline variation and installation. For these reasons, it is advisable to provide them with the equivalent of a 10 pipe diameter straight upstream run, to use dampers if pipe vibration or pulsating flow is expected, and to readjust their settings if they are to be mounted in vertical upward flow lines. The conventional paddle-type designs are incapable of distinguishing low flow velocities from no-flow conditions. Therefore, if low flows are to be detected, the folding circular paddle should be used, which permits the full diameter paddle to fold back upon itself, to minimize pressure drop.

**1.6.5.1.2 Swinging Vane Design**

In smaller sized pipelines where it is desired to provide local flow indication, in addition to the flow switch action, the variable area type flow switches can be considered. If the vertical upward flow configuration of the rotameter design is not convenient from a piping layout point of view, the circular, swinging vane design, shown in Fig. 1.73 can be considered.

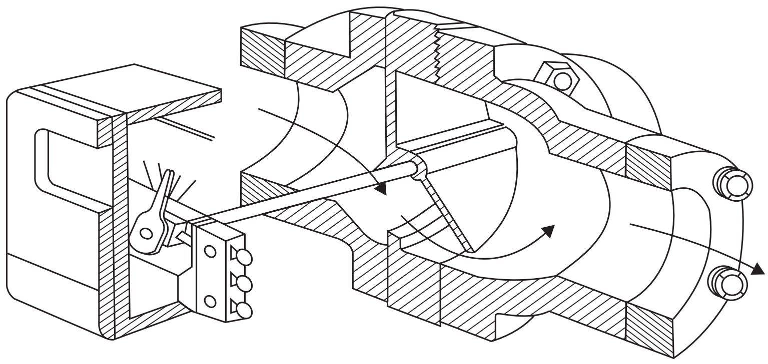


**Fig. 1.73** Swinging vane flow switch

**1.6.5.1.3. Capacitance-Type Flow Switch**

If the purpose of the flow switch is to protect pumps from running dry, the wafer-type capacitance insert unit is a good choice which is shown in Fig. 1.74.

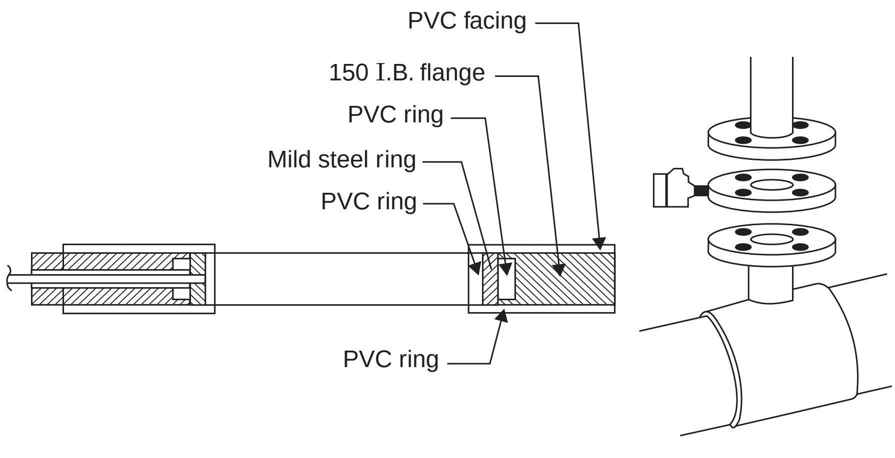



**Fig. 1.74** Capacitance type flow/no-flow switch

**1.6.5.1.4 Thermal Flow Switch**

Flow switch reliability is increased by the elimination of moving parts, so that pipe vibration or fluid flow pulses will not cause erroneous switch actuation. One of the most popular solid-state designs is the thermal flow switch which is shown in Fig. 1.75.

All heat actuated flow switches sense the movement or stoppage of the process stream by detecting the cooling effect (temperature change) on one or more probes. They are available both in the flow through and in the probe configuration. One design consists of a heater probe and two sensor probes, connected in a wheatstone bridge. When the flow stops, an imbalance in the bridge circuit occurs.

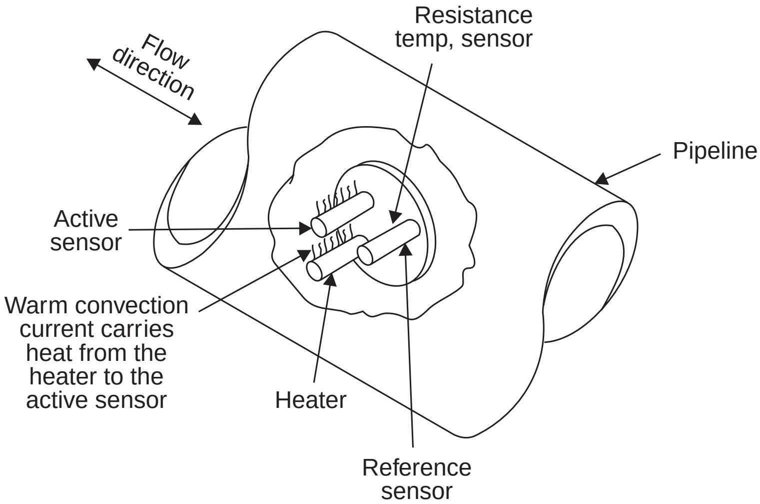



**Fig. 1.75** Thermal flow switch

The main advantage of this design is its ability to detect very low flow velocities. Its main limitation is that it cannot respond instantaneously to flow changes. Depending on switch adjustments and on type of process fluid, the speed of response will vary from 2 seconds to 2 minutes.

#### 1.6.5.1.5 Bypass Flow Switch

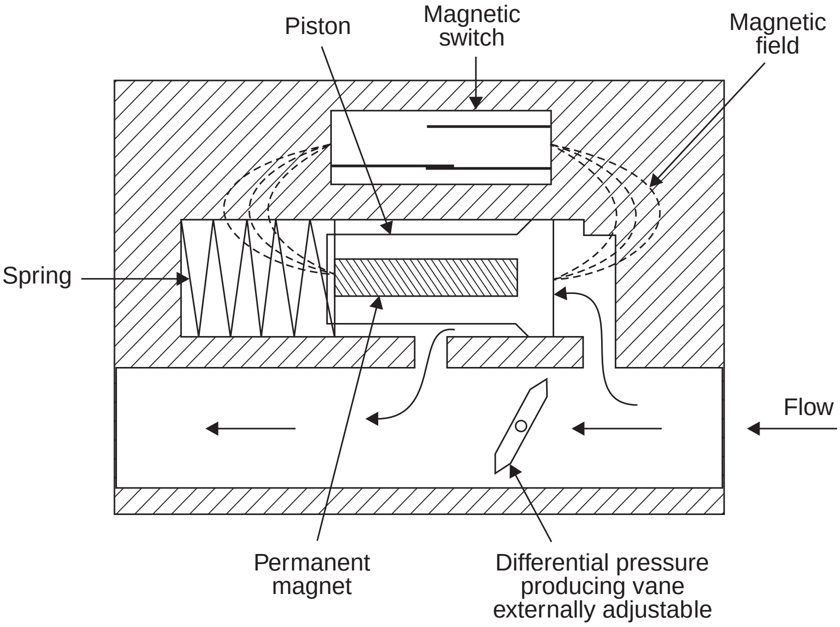



**Fig. 1.76** Bypass flow switch

A bypass-type switch shown in Fig. 1.76 has an externally adjustable vane that creates a differential pressure in the flow stream. This differential pressure forces a proportional flow through the tubing that bypasses the vane. A piston retained by a spring is in the bypass tubing and will move laterally as flow increases or decreases ; the piston's movement activates a switch. Bypass flow switches can be used for fairly low flow rates and their ability to be externally adjusted is a desirable feature.

## 1.6.6 Anemometers

The use of hot wire resistance transducer is to measure the flow rate of fluids by means of measuring velocity of non conducting liquids. In open channels and closed pipes it can be conveniently measured by suitably locating the hot wire filament.

### 1.6.6.1 Hot Wire Filament

Hot wire filament is usually made by wire of platinum or tungsten material. It is suitably mounted in the flow channel by means of a support as shown in Fig. 1.77. The diameter of the wire may vary from 5 μm to 300 μm and the length is about half the diameter of the pipe. A smaller diameter gives a larger resistance per unit length and less inertia but is also less capable of sustaining large fluid pressure. The capability of its withstanding large pressure shocks is decided after actual testing. The hot wire element is centrally located inside the pipe such that the axis of the wire is normal to the direction of fluid flow.

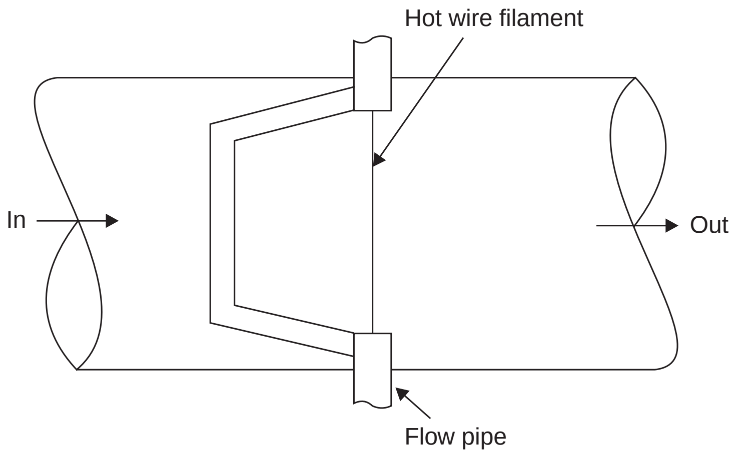



**Fig. 1.77** Hot wire filament

### 1.6.6.2 Principle

In hot wire anemometers, the filament is heated initially by means of passing an electric current. This heated resistive filament mounted on a tube is exposed to air flow or wind, which is cooled because of fanning effect. Depending on the velocity of air flow, the amount of cooling varies. The resistance of the probe when it is hot is different from that when it is cooled. This difference in resistance or this variation in resistance is converted into a voltage variation and thereby the flow velocity is converted into a voltage variation.

### 1.6.6.3 Types of Hot Wire Anemometers

Hot wire anemometers are commonly available in two forms :

(*i*) Constant current type and

(*ii*) Constant temperature type.

Both utilize the same physical principle but in different ways.

#### 1.6.6.3.1 Constant Current Type

In the constant—current mode of operation, the current through the hot wire is kept constant at a suitable value. The measuring circuit of this type is shown in Fig. 1.78(*a*).

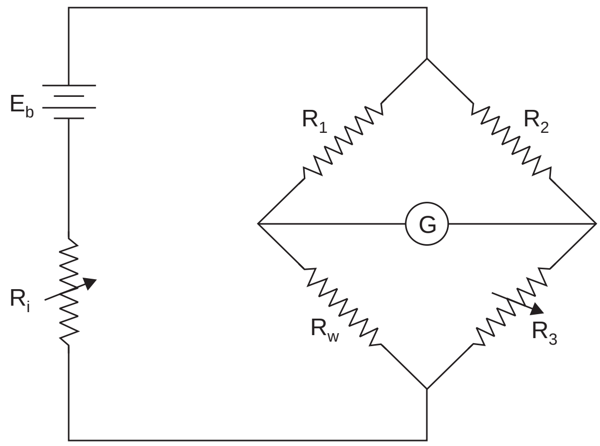



**Fig. 1.78** (a) Measuring circuit of a constant current type

In this type, the hot wire resistive filament which is mounted centrally in the flow pipe, carrying a fixed current is exposed to the flow velocity. The hot wire filament attains an equilibrium temperature when the $i^2$R heat generated in it is just balanced by the heat loss from its surface. The proper circuit design is needed so that $i^2$R heat is essentially constant. Thus the hot wire filament temperature must adjust itself to change the heat loss until the equilibrium is reached and this equilibrium wire temperature is a measure of velocity. The wire temperature can be measured in forms of its electrical resistance.

$$R_i > 2\ K\,\Omega$$

$$R_1, R_2, R_3 \quad \text{and} \quad R_w \cong 1 \text{ to } 2\ \Omega$$

Energy balance equation for equilibrium conditions is written as

$$i^2 R_w = hA(T_w - T_f)$$

where $i$ = Hot wire current

$R_w$ = Wire resistance

$T_w$ = Wire temperature

$T_f$ = Temperature of flowing fluid

$h$ = Film coefficient of heat transfer

A = Heat transfer area.

The measuring circuit of the constant-current anemometer can be used for the measurement of steady velocities as well as rapidly fluctuating components such as turbulent components superimposed on an average velocity.

#### 1.6.6.3.2 Constant-Temperature Type

The current through the hot wire filament is adjusted to keep the wire temperature constant in this type. A galvanometer is used to detect the balance conditions. The bridge is connected to a battery voltage source in series with an adjustable resistor of a very large value (2KΩ). The voltage drop across the hot wire filament is measured by a high resistance millivoltmeter whenever the bridge is brought to balance condition.

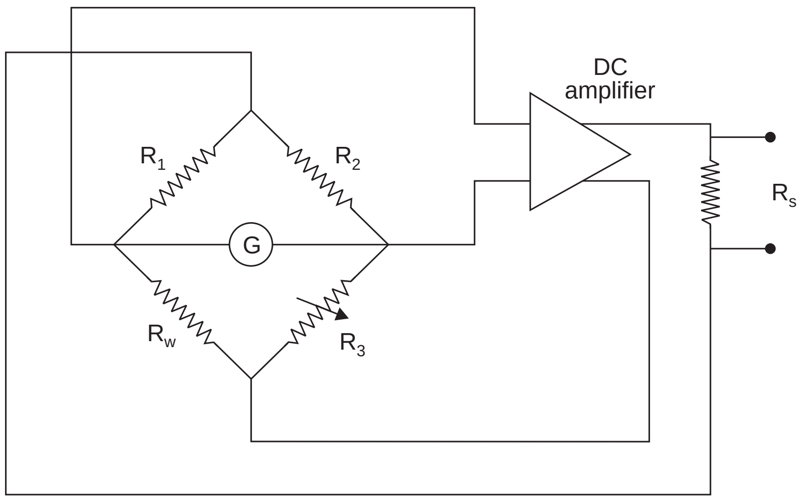



**Fig. 1.78** (b) Measuring circuit of a constant temperature type

The measuring circuit is shown in Fig. 1.78 (*b*) . When there is no flow, the bridge is in balance condition. For a change in flow, resistance of the hot wire ($R_w$) changes and the bridge is unbalanced. The unbalanced voltage is amplified and is used as a supply to the bridge. The bridge current required for balancing gives the change in the flow velocity. This current is measured by measuring the voltage across the standard resistance $R_s$.

When the resistance of hot wire filament $R_w$ is maintained constant by adjusting $R_s$, the current through the ammeter in series with $R_w$ is obtained for varying the voltage V. The variation of the current $I^2$ as a function of the voltage $\sqrt{V}$ is shown in Fig. 1.79. It is called as calibration curve.

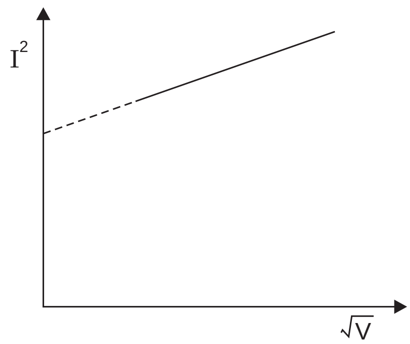



**Fig. 1.79** Variation of $I^2$ with respect to $\sqrt{V}$

### 1.6.6.4 Comparison Between Constant-Current Type And Constant-Temperature Type

In constant current type, the current has to be kept at a large value and if sudden drop in velocity of fluid/gas occurs, the convection loss is very much reduced and thereby resulting in burning out of the hot wire filament.

In constant-temperature type, the disadvantages are the instability and drift problems in the amplifier design and high noise figure obscuring measurements of very small velocity fluctuations.

### 1.6.7 Mechanical 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.

#### 1.6.7.1 Vane Anemometer

Fig. 1.80 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 capacitively coupled pickup can be used to generate a transmission signal.

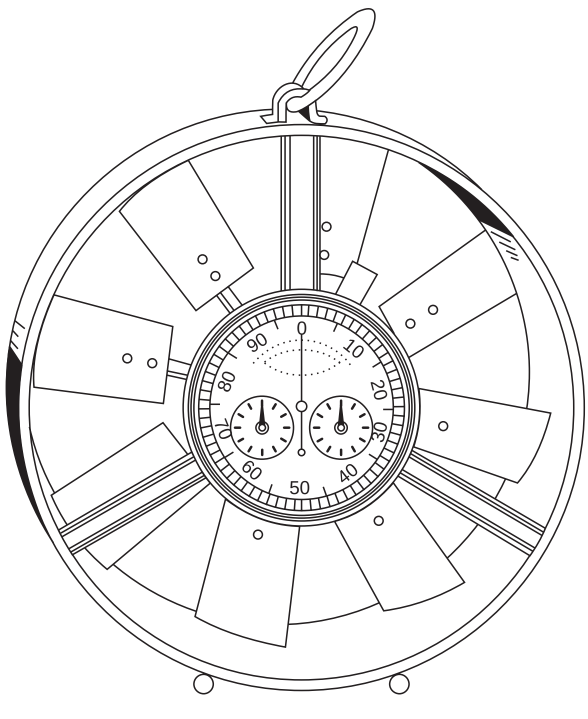



**Fig. 1.80** Vane design anemometer

#### 1.6.7.2 Three-Cup Anemometer

Fig. 1.81 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.

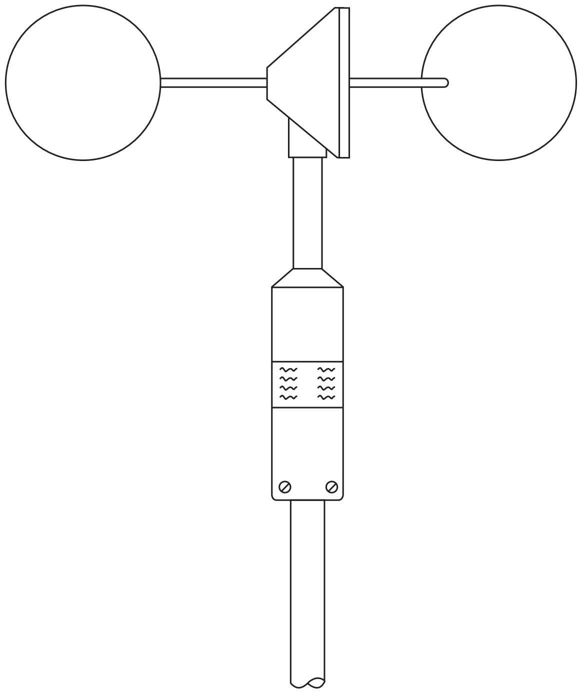


**Fig. 1.81** Three cup-anemometer.

### 1.6.7.3 Impeller Anemometer

The impeller design is shown in Fig. 1.82. 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.

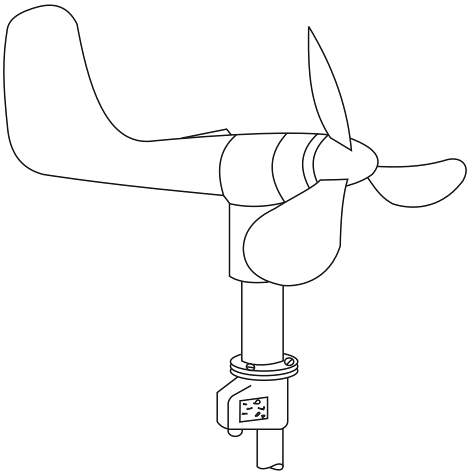


**Fig. 1.82** Impeller-anemometer.

## 1.7 Flow Meter Calibration

### 1.7.1 Introduction

Flow rate calibration depends on standards of volume and time or mass and time. Primary calibration is generally based on the establishment of steady flow through the flow meter to be calibrated and subsequent measurement of the volume or mass of the flowing fluid that passes through in an accurate time interval. If steady flow exists, the volume or mass flow rate may be inferred from such a procedure. As in any other calibration, significant deviations of the conditions of use from those at calibration will invalidate the calibration. Possible sources of error in flow meters include variations in fluid properties (density, viscosity and temperature), orientation of meter, pressure level, flow disturbance (such as elbows, tees, valves etc) upstream to the meter.

### 1.7.2 Methods of Calibration of Flow Meter With Liquids

**1.7.2.1 Dynamic Weighing (Gravimetric) Method**

A commercial calibrator for precise primary calibration of flow meters using liquids is shown in Fig. 1.83. These units use a convenient dynamic weighing scheme, and are available in different models to cover the range from 0.5 to 70,000 kg/hr and have an overall accuracy of ± 0.1%. The sequence of the calibration procedure is explained below :

**(a) Running operation before Test : Fig. 1.83(a)**

Fluid contained in the reservoir is pumped through a closed hydraulic circuit. First, it enters the filter and then the heat exchanger equipment, which controls temperature within ± 20°C. It then passes through the control valves, the meter under test, the back pressure valve, the weigh tank, and then back into the reservoir.

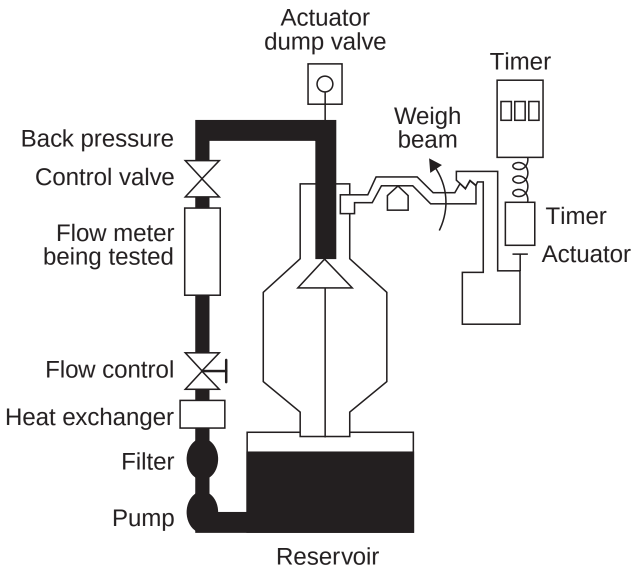



**Fig. 1.83** (*a*)

**(b) Start of preliminary fill : Fig. 1.83(b)**

When the control valves have been adjusted for desired flow, a tare weight is placed on the weigh pan. Then the cycle start button is pushed, resetting the timer, closing the dump valve which starts the filling of the weigh tank.

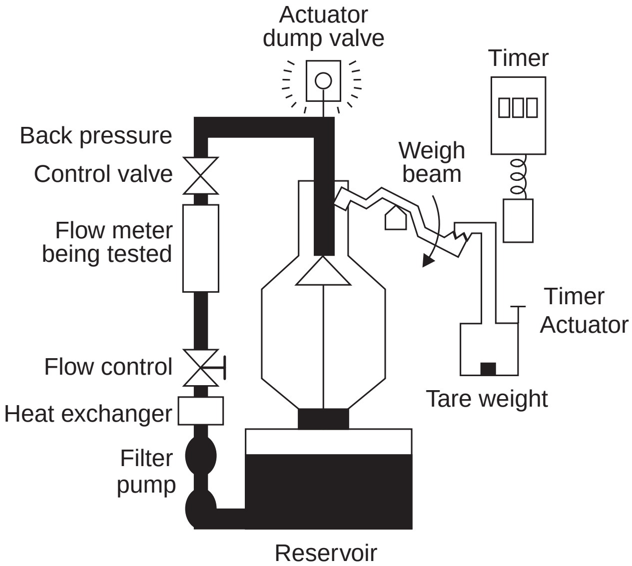



**Fig. 1.83** (*b*)

**(c) End of the pre-fill, start of weighing cycle : Fig. 1.83(c)**

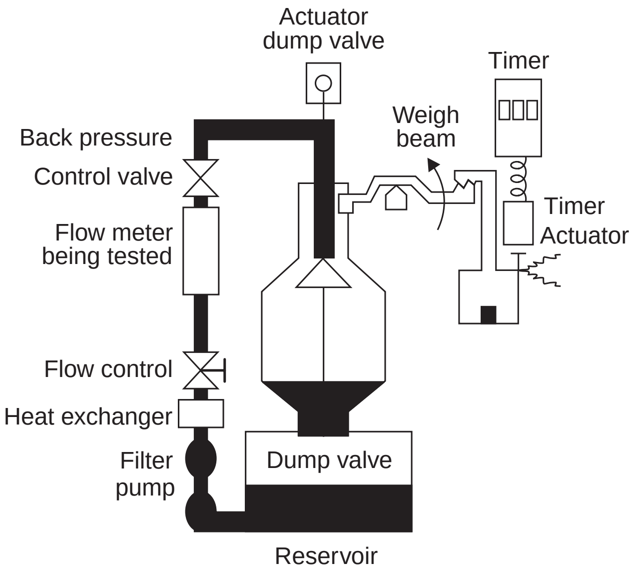



**Fig. 1.83** (*c*)

As the weigh tank fills, the weigh pan rises, tripping the timer actuator, and the electronic timer begins counting in milliseconds, starting the actual weighing cycle. The preliminary fill balanced out by the tare weight before actual weighing begins, permits a net measurement of the new fluid added after preliminary fill. The preliminary fill method permits the measurement of only a portion of the cycle, eliminating the mechanical errors in the start and stop portions and allowing dynamic errors to be self cancelling.

**(d) Weighing cycle in Operation : Fig. 1.83(d)**

The weighing cycle is continued as a precision weight is placed on the weigh pan, again deflecting the beam. The uniquely designed cone shaped deflector at the inlet of the weigh tank permits the even distribution of measured fluid.

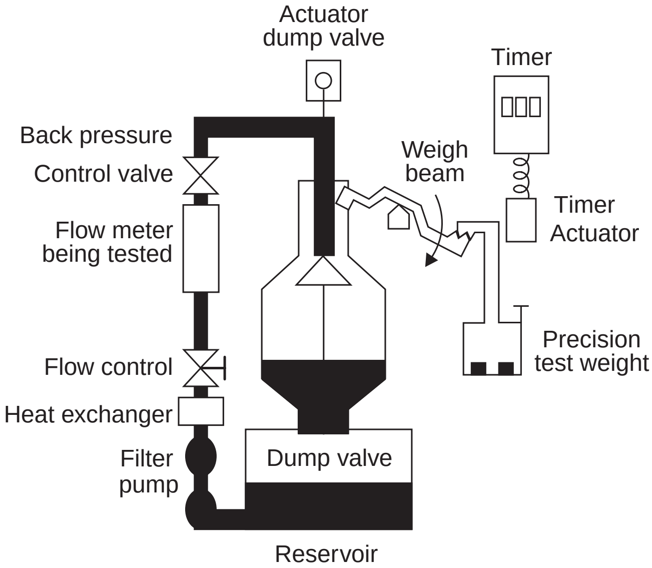



**Fig. 1.83** (*d*)

**(e) End of Weighing Cycle : Fig. 1.83(e)**

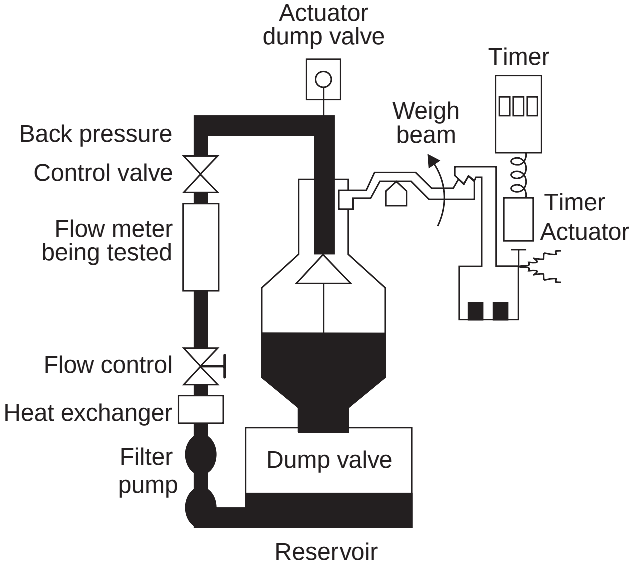



**Fig. 1.83** (*e*)

As the tank fills, the weigh pan rises, until it again trips the timer actuator, stopping the timer and the indicating the time within a thousandth of a second. By combining the precision test weight with the timed interval, the actual flow rate in kg/hr is easily and accurately determined. From these basic mass units, other flow units can be accurately calculated.

**(f) Emptying for Recycling : Fig. 1.83(f)**

After the beam movement trips the timer, the weigh tank automatically empties in less than 25 seconds, even at maximum flow. The calibrator is now ready for the next flow setting. This fast recycling cuts total calibrating time as much as 50%.

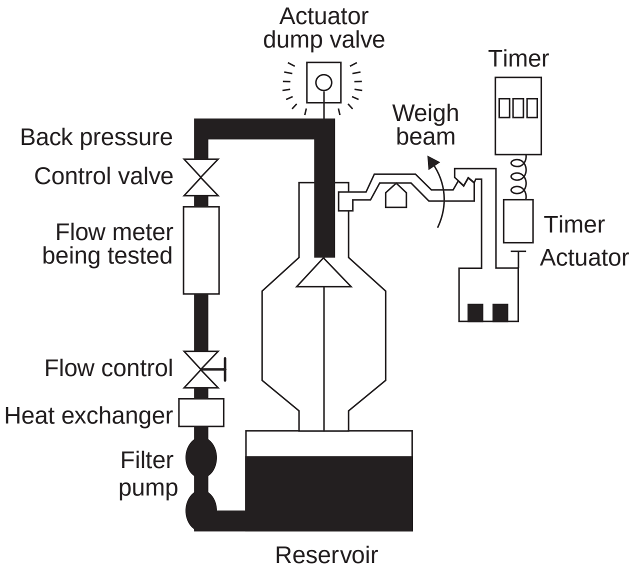



**Fig. 1.83** (*f*)

### 1.7.2.2 Pipe Prover Method

Another type of calibrator called pipe prover is particularly useful for fast response, high resolution flow meters such as turbine, positive displacement, vortex shedding types, where steady state can be achieved quickly. The integration of the flow rate to get total flow is accomplished accurately by accumulating the meter pulse-rate output in counter. Although they can be used with flow rate meters, in practice their use is largely confined to the calibration of quantity meters. A 'dedicated prover' is permanently built in large petroleum metering stations.

One such pipe prover (bidirectional) which is currently most popular is shown in Fig. 1.84.

A hollow sphere of synthetic rubber is inflated with water under pressure until its diameter is about 2% larger than that of the epoxy-liner pipe from which the prover is constructed. When the sphere is forced into the pipe, it seals it and acts as a kind of piston which is capable of going round the bends. A four way valve is used to control the flow of liquid after it has passed through the meter which is to be calibrated, by causing the liquid to travel through the prover either from left to right or from right to left. At either end of the prover there is a chamber of enlarged diameter to receive the sphere at the end of each trip.

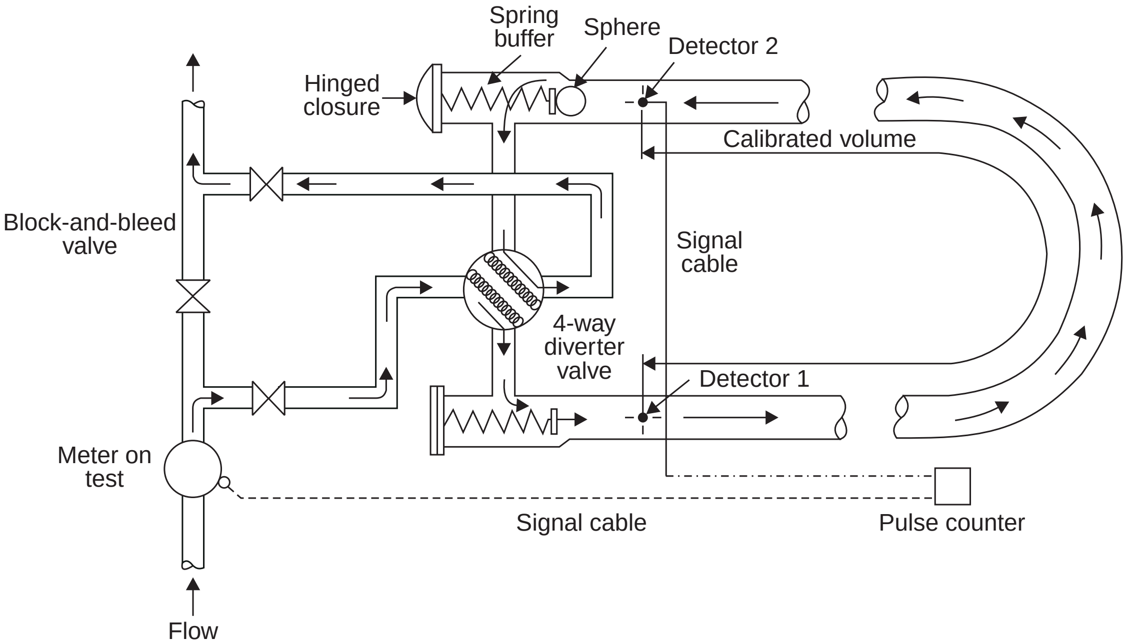



**Fig. 1.84** Principle of the bidirectional pipe prover

Before starting the calibration run, the flow is allowed to by-pass the prover. At the start of a test, the flow is directed through the prover in such a way that the sphere travels the whole length of the prover. Soon after the start of its run, it passes a sphere detector, which operates an electrical gating circuit and causes the electrical pulse from the meter on test to be counted. Near the end of the run, a second sphere detector is operated which stops the count of pulses. The pulse count from the meter is then compared with the known volume of the prover between sphere detectors, which has been determined from a previous static calibration of the prover. Additional accuracy is gained by totalising the pulse counts and the prover volumes during two successive runs one in each direction. Directional effects in the sphere detectors are thus largely cancelled out.

The accuracy of the bidirectional prover is as high as ± 0.1% of flow rate and between ± 0.05 and ± 0.02% on total volume.

**1.7.2.3 Master Meters Method**

The simplest and cheapest way of calibrating a flow meter is to put it in series with another flow meter of higher accuracy and to compare their readings. This can give reasonably accurate results over a short period, provided that care is taken to install the two meters sufficiently far apart to ensure that the downstream meter is not affected by the presence of the upstream meter. A serious disadvantage of the method is that the performance of the master meter will gradually change with time ; consequently, recalibration of the master meter will be needed at intervals.

Also if the master meter should suffer any kind of sudden mechanical wear, its performance could change in a very short period without the operator being aware of the fact. As a safeguard against this happening, it is possible to use two master meters in series as shown in Fig. 1.85.

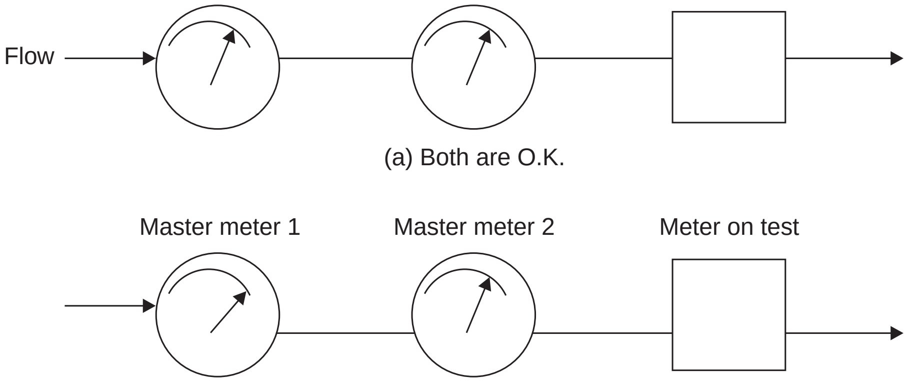



**Fig. 1.85** Two master meters are in series

A long as the two meters continue to give the same reading the operator can be confident that all are well, but as soon as one master meter gives a significantly different reading from the other, he knows that one meter is malfunctioning. The rig must then be shut down while both meters are removed for recalibration.

To avoid having to shut down the rig in circumstances like this, three master meters can be installed in series. In this case, the malfunctioning meter will immediately betray itself by showing that it is out of step with the other two. The defective master meter can then be taken out of the line and sent away for recalibration, while the operator continues to use his rig with the other two master meters in operation.

A third alternative is to use two master meters in parallel, with high-fidelity shut-off valves, as shown in Fig. 1.86.

This system is suitable only when meters of high repeatability, such as large turbine meters, are to be calibrated, because the meter of test provides the only way to

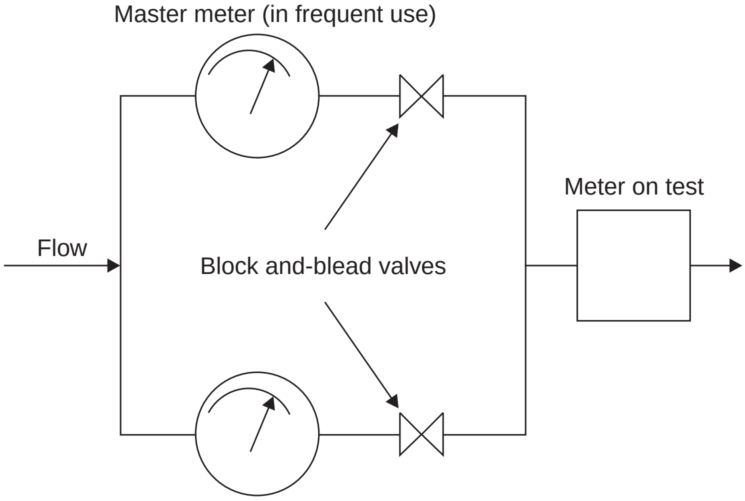



**Fig. 1.86** The use of two Master meters in alternate parallel

compare the performances of the two master meters. One master is used as the main calibration device, while the other master meter as a 'super master meter,' being used alternately with the first master meter on infrequent occasions as a check that the master meter, remains unchanged. As soon as a change in the performance of the master meter is observed it is removed for recalibration. When it is fitted back after recalibration it is regarded as the super master meter, while the other meter becomes the master meter. This situation remains until another recalibration is called for, when the roles of the two meters are again reversed.

A well maintained master meter calibration system should provide accuracies of ± 0.2% on flow rate and ± 0.1% or ± 0.5% on volume.

### 1.7.3 Methods of Calibrating Flow Meters With Gases

#### 1.7.3.1 Soap Film Burettes

It is suitable only for low flow rates, since it is difficult to form a stable soap film across a burette of more than about 50 mm diameter. The film is made to act as a frictionless 'piston' which travels freely with the flowing stream of gas, so that the velocity of the film is a good indication of the velocity of the flowing gas. Fig. 1.87.

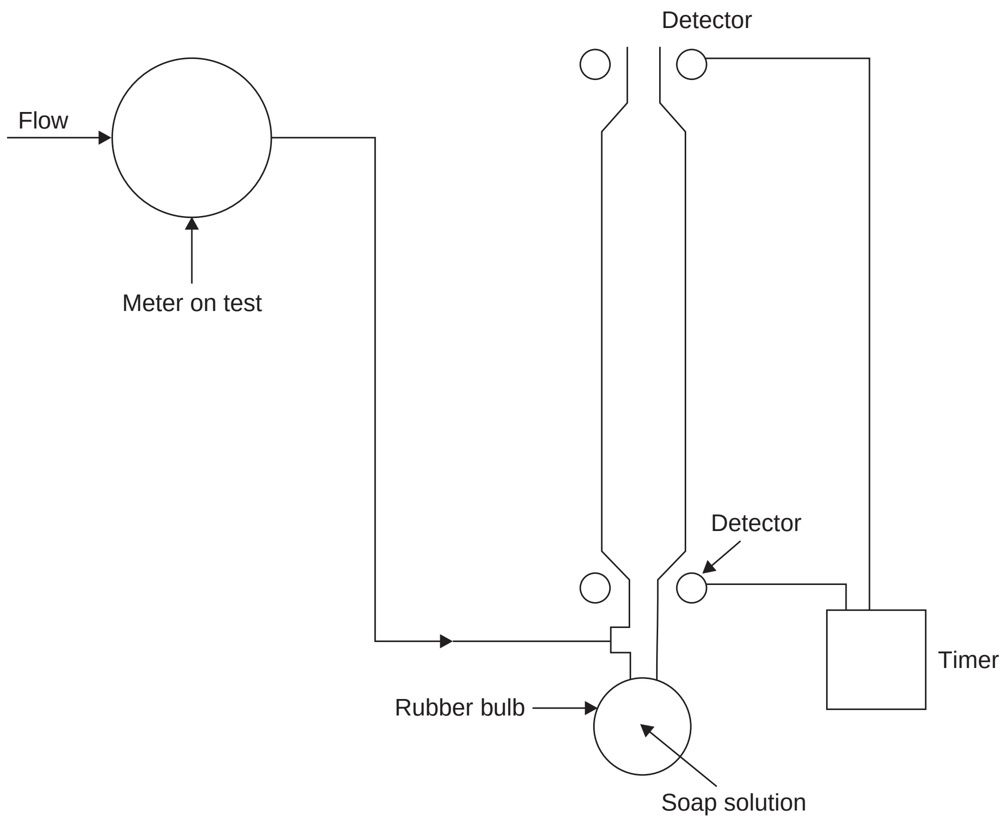



**Fig. 1.87** Principle of the Soap-film burette

The soap film burette can be used to calibrate both flow rate and quantity meters. It will measure flow rate with an accuracy of ± 0.5% and volume with an accuracy between ± 0.5% and ± 0.2%.

### 1.7.3.2 Bell Prover System

Bell prover system for calibrating gas flow meter is shown in Fig. 1.88.

The gas flowing through the flow meter during a timed interval is trapped in gasometer bell and its volume is measured. Temperature and pressure measurements allow calculation of mass and conversion of volume to any desired standard conditions. By filling the bell with gas, rising it to the top, and adding appropriate weights, such a system may be used as a gas supply to drive gas through a flow meter as the bell gradually drops at a measured rate. By using a precision analytical balance to measure the mass accumulated in storage vessel over time, accuracies, of ± 0.02% were obtained for flow rate upto 9 kg/sec.

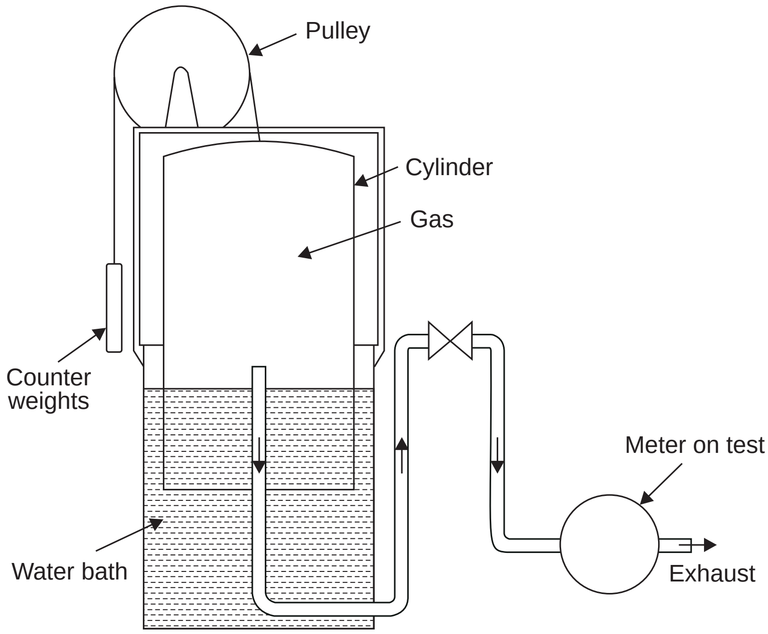



**Fig. 1.88** Simplified schematic arrangement of bell prover system for calibrating small gas quantity meters

### 1.7.3.3 Sonic Venturi-Nozzles

The Sonic Venturi-nozzle is a very convenient device for calibrating a gas flow rate meter at one volumetric flow rate. Fig. 1.89.

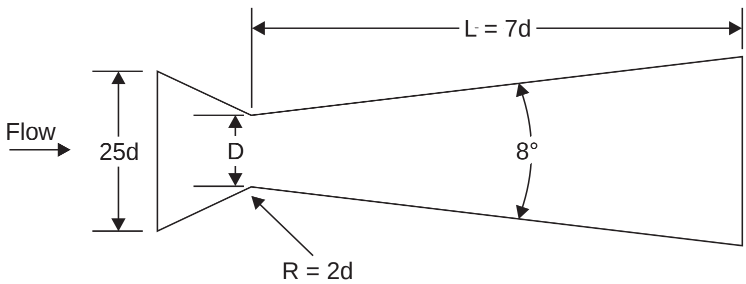



**Fig. 1.89** Standard sonic venturi-nozzle

It depends upon the fact that in the throat of a nozzle, the gas cannot travel faster than the speed of sound. Provided the upstream pressure is sufficient to ensure that sonic velocity is actually reached, the flow rate through the nozzle will therefore always have a fixed value for a given gas at a specified temperature and pressure. The tapered section of the nozzle plays no part in controlling the flow rate ; its function is merely to assist, in recovering some 90-95% of the initial pressure, thus conserving energy.

If a number of sonic venturi nozzles of various sizes are used in succession a gas flow meter can be calibrated over a range of flow rates with them. When the highest possible accuracies (about ± 0.5% on flow rate) are called for it is usual for venturi—nozzles to be calibrated against a primary gas flow standard before they are used as calibration devices. If slightly lower accuracies are acceptable their performance can be predicted fairly reliably from a knowledge of their dimensions.

### 1.7.3.4 Gravimetric System for Gas-Meter Calibrator

The gravimetric calibration is a highly sophisticated and expensive device, but is regarded as the best available primary system for calibrating secondary high-pressure gas flow standards. It can also be used directly for the calibration of high-pressure gas meters. It is broadly similar in principle to the gravimetric system with static weighing for liquids, but with one important difference. In the liquid system the meter being calibrated is at upstream of the flow diverted, but in the gas system it is at downstream and in a line venting to atmosphere. This enables the meter to be read under steady-state conditions, thus overcoming the problem of diminishing flow rate, which occurs while the weighing vessel is being filled.

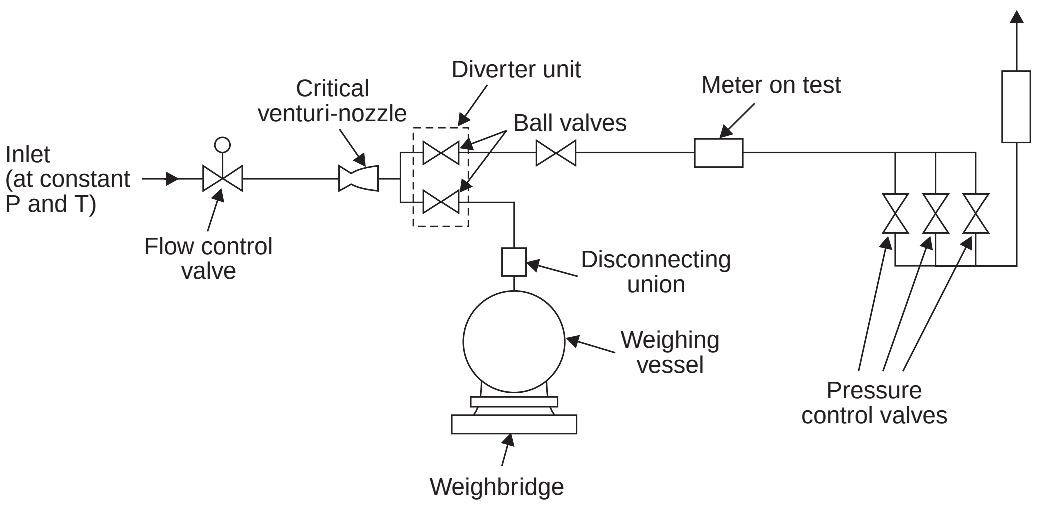



**Fig. 1.90** Simplified Arrangement of a Gravimetric system for compressed gases

As shown in Fig. 1.90, a critical venturi-nozzle is used to maintain a constant flow rate through the test system. In the first part of the test, the flow at downstream of this nozzle is diverted through the meter being calibrated, while its reading is noted. Then the flow is diverted into a light weight spherical pressure vessel for a measured time, and the measurements of the weight of this sphere before and after diversion are used to calculate the mass flow rate during the diversion period. By varying the pressure upstream of the critical venturi-nozzle, a fairly wide range of mass flow rates can be covered with this system, and by using several alternative nozzles of different sizes, an almost unlimited range can be covered.

The accuracy of flow rate measurement in a system of this kind is between ± 0.5% and ± 0.2%.

### 1.7.3.5 PVT System

The PVT (Pressure-Volume-Temperature) method illustrated in Fig. 1.91 is used mainly as a primary standard, to calibrate reference meters and sonic venturi nozzles which can thereafter be used as secondary calibration devices.

In this system, a storage vessel of known volume is charged with gas at high pressure. The pressure and temperature of the gas in the vessel are first measured, then the gas is allowed to flow out through a regulating sonic nozzle in series with the meter on test, and finally the pressure and temperature of the gas in the storage vessel are measured again at the end of a measured period of time.

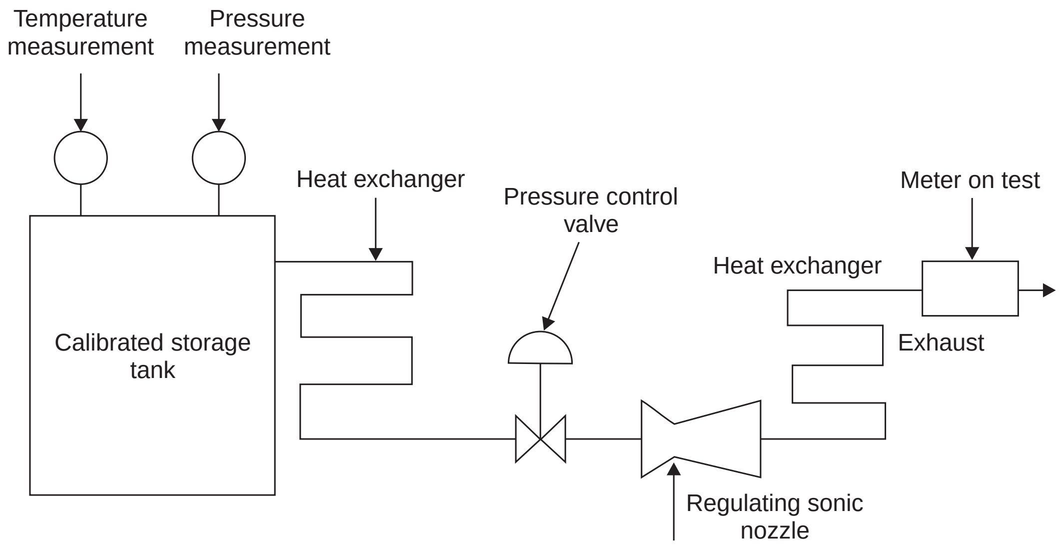



**Fig. 1.91** PVT System

From these measurements the mass flow rate through the system during the test period can be calculated. Heat exchangers and an upstream pressure controller are used to control the conditions during flow and thus the performance of the meter under test can be determined over a wide range. Accuracies of flow rate measurement between ± 0.5% and ± 0.2% can be achieved.

## 1.8 Flow Meter Selection

The selection of a flow meter for an industrial application is influenced by complex desired data. While purchasing a flow meter, it is better to get advice from an expert on the selection based on the availability of flow meter and draw out a complete specification of the flow metering application.

### 1.8.1 Factors to be Considered

There are many factors which are to be considered before drawing up specifications for a flow meter. They are :

1. Measurement requirements
2. External conditions of the flow pipe
3. Internal conditions of the flow pipe
4. Properties of the flowing fluid
5. Installation and accessories and
6. Cost consideration.

Let us examine the above six factors in detail.

#### 1.8.1.1 Measurement Requirements

The requirements of measurement can be addressed based on.

(*i*) The measured variable like point velocity, average velocity or volume rate.

(*ii*) **The range of operation.** For wide range of operation, electromagnetic, ultrasonic, cross-correlation, turbine type etc. are suitable.

(*iii*) **Cost computation.** If it is for costing purpose, the meter should have low and consistent uncertainty in measurement.

(*iv*) **Pressure head loss and maximum pressure of flowing fluid.** For high pressure fluids the meter body and inner construction should be sturdy.

(*v*) Accuracy, Precision and facilities available for maintenance.

(*vi*) **Speed of response.** For fluctuating flow, response of the meter should be good with small time constants.

(*vii*) Calibration facilities and Installation.

#### 1.8.1.2 External Conditions of the Flow Pipe

Before selection of a flow meter, it is important to examine the environment and the place where the meter is going to get installed. The following points need to be considered.

(*i*) **Approachability.** It is better to know that once the meter is installed whether it is accessible for removal, recalibration etc.

(*ii*) It is important to note that the installation of the meter either in an air conditioned space or in a place which is vulnerable for wide temperature variation.

(*iii*) Humidity condition, vibration, hostile environment and water facility are the important parameters to be considered.

#### 1.8.1.3 Conditions Internal to the Flow Pipe

The conditions internal to the pipe affect the accuracy of measurement of flow meters. Some of the factors that affect the accuracy are protrusions, pipe bore, size, roundness, toughness, hydrodynamic noise pulsations etc.

### 1.8.1.4 Properties of the Fluid

The properties of the fluid to be metered should be clearly understood by the person who is to select the meter. Many flow problems are due to the impurities present in the fluid, the effect of which cannot always be quantitatively established.

1. **Viscosity.** Viscosity of the flowing fluid is a critical factor. If the viscosity of the fluid changes, the Reynolds number changes, which in turn affect the calibration curve of the flow meter.

2. **Fluid activity.** The fluid to be metered may be radioactive or chemically reactive. Radioactivity presents special problems. For metering the velocity of fluids having high levels of radiation, flow meters offering long periods of reliable operation without maintenance are required. If the fluid is corrosive, then Electromagnetic flow meter or Vortex flow meter can be used.

3. **Flammability.** Fluids which are inflammable or react violently with other materials need flow meters like turbine and vortex flow meter. They are suitable for operation in hazardous areas.

4. **Scaling Deposits.** Special care should be taken for fluids having a property to deposit scales since scaling can block pressure lines and ducts.

5. **Other properties.** The fluid properties like compressibility, abrasiveness, transparency, electrical conductivity, magnetic properties and lubricity should be noted before selection of flow meter is made.

### 1.8.1.5 Accessories

When a flow meter is chosen, the associated accessories should also be chosen which are compatible with the meter. All the precautions and points considered for the meter should be considered for the accessories also. Some of the accessories for a flow meter are :

1. Valves and manifolds for equalizing, draining, venting and isolation.
2. Sumps, gas vents, poles and drains.
3. Cooling chambers when measuring condensible vapours.
4. Straighteners for improving velocity profile.
5. Piezometer rings for averaging the flow velocity profile for orifice plates.
6. Separators to prevent contaminating fluids like water in oil from entering the flow meter.
7. Gas detectors to provide a warning if the flow meter is not running full.

### 1.8.1.6 Economic Factors

Any decision on the purchase or selection of flow meter will certainly take the economic factors into consideration. But that should not be given the top priority. When computing the cost of flow meters, the cost of accessories, transmitters etc. if needed, the maintenance cost for a period should also be taken into consideration.

### 1.8.2 List of Desirable Characteristics

A partial list of characteristics that are desirable in a flow meter selection is given below :

(*i*) A wide operating temperature range.

(*ii*) A wide dynamic range of measurement.

(*iii*) Insensitivity to flow profit, viscosity, and other physical properties of the fluid.

(*iv*) Non-corrodible and non-degradable materials of construction.

(*v*) Small irrecoverable head loss.

(*vi*) Suitability for liquids and gases.

(*vii*) Availability in all practical sizes.

(*viii*) Safety in all practical sizes.

(*ix*) Immunity to pulsating flow effects.

(*x*) Immunity to vibration.

(*xi*) Fast response to flow changes.

(*xii*) Accuracy.

(*xiii*) Calibration.

(*xiv*) Low cost to purchase and maintain.

Of course, no flow meter is available which meets all these requirements and it is unlikely that one will ever be developed.

### 1.8.3 Highest Possible Accuracy

| | | | |
|---|---|---|---|
| 1. | ORIFICE | ± | 2.0% |
| 2. | VENTURI | ± | 1.0% |
| 3. | NOZZLE | ± | 1.5% |
| 4. | PITOT | ± | 0.5% |
| 5. | EM | ± | 0.5% |
| 6. | UF | ± | 1.0% |
| 7. | CC | ± | 0.5% |
| 8. | VS | ± | 1.0% |
| 9. | ROTAMETER | ± | 2.0% |
| 10. | HOTWIRE | ± | 2.0% |
| 11. | GILFLOW | ± | 1.0% |
| 12. | NMR | ± | 0.5% |
| 13. | LDU | ± | 0.05% |
| 14. | PD | ± | 0.1% |
| 15. | TURBINE | ± | 2.0% |
| 16. | MASSFLOW | ± | 1.0% |

### 1.8.4 Guidelines for Flow Meter Selection

In Summary, Table 1.1 gives the guidelines for flow meter selection and Table 1.2 gives the application details of various flow meters.

Guide to Flowmeter Selection

**Table 1.1**

| *Property* | *Rotameter* | *Orifice* | *Turbine* | *EM Flow Meter* |
|---|---|---|---|---|
| Service | Liquid and Gases | Liquid and Gases | Liquid and Gases | Electrically conducting liquid and slurries |
| Liquid Flow Limits | 0.01 cc/m 16000 l/m | 0.1 cm/m Large | 0.001 cc/m 160000 l/m | 0.01 cc/m 2000000 l/m |
| Gases at air Equivalent at STP | 0.3 cc/m 40,000 l/m | 50 cc/m onwards | upto 10,000,000 50,00000 l/m | |
| Scale or Signal Charac. | Linear or Log | Square root | Linear for Reynolds no. 100000 | Linear |
| Range | 5 : 1 to 12 : 1 | 4 : 1 | 10 : 1 to 15 : 1 | 10 : 1 |
| Range with span adjusted | 12 : 1 float to be changed | 12 : 1 | 15 : 1 and more | 100 : 1 |
| Accuracy | + 2% FS if calibrated | + 1% FS (uncalibrated) | + 0.25% of reading | + 0.5% reading |
| Transmitter Types | Visual or Analog Pneumatic | Analog Pneumatic or Elec. | Analog Elec. Digital | Analog Elect. Digital |
| Maximum overall Pr. Loss | 1 – 10 m of $H_2O$ | 3 – 60 m of $H_2O$ | 10 – 40 m of $H_2O$ | Negligible |
| Viscosity | Good Immunity | Fairly good Immunity | Fairly good Immunity | No effect |

**Table 1.2** Flow Meter Application Table

| S. No | Flow Meter Types Appli-cations | Water | Solids in Liquid | High Pres. Gases | Low pres. Gases | Larger Meter Pipes | Large Air Ducts | Low Water Flow | Low Gas Flow | Hot Liquids | Hot Gases | Cyogenic Fluids | High Viscous | Low Viscous |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Venturi | ✓ | | ✓ | ✓ | ✓ | | | | ✓ | | | | ✓ |
| 2 | Orifice | ✓ | ✓ | ✓ | ✓ | | | | | ✓ | ✓ | | ✓ | ✓ |
| 3 | Nozzle | ✓ | | ✓ | ✓ | | | | | ✓ | ✓ | | | |
| 4 | Target | | ✓ | | | | | | | ✓ | ✓ | | | |
| 5 | Rotameter | ✓ | | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | | | ✓ |
| 6 | Spring Loaded Lower Rotameter | ✓ | | ✓ | | | | ✓ | | ✓ | | | ✓ | ✓ |
| 7 | Turbine | ✓ | | ✓ | | | | | | | | | | ✓ |
| 8 | Bypass Rotameter | ✓ | | ✓ | | | | | | ✓ | ✓ | | | ✓ |
| 9 | EM | ✓ | ✓ | | | ✓ | | ✓ | | ✓ | | | ✓ | |
| 10 | UF | ✓ | ✓ | | | ✓ | | | | | | | | ✓ |
| 11 | VS | ✓ | | ✓ | | | | | | | | ✓ | | ✓ |
| 12 | Fluidic | | | | | | | ✓ | | | | | | ✓ |
| 13 | Swirl | | | ✓ | | | | | | | | | | |
| 14 | NMR | | ✓ | | | | | | | | | | ✓ | ✓ |
| 15 | Mass | | | | | | | ✓ | | ✓ | | ✓ | ✓ | ✓ |
| 16 | Hot wire | | | ✓ | ✓ | | ✓ | | ✓ | | | | | |
| 17 | Insertion | ✓ | | ✓ | ✓ | ✓ | ✓ | | | | ✓ | | | |
| 18 | CC | | ✓ | | | | | | | | ✓ | | | ✓ |
| 19 | PD | | | | ✓ | ✓ | | | | | | ✓ | ✓ | ✓ |

## 1.9 Problems and Solutions

**Problem 1.** Water is pumped through a 75 mm diameter pipe with a flow velocity of 760 mm/sec. Find the volume flow rate and mass flow rate. Density of the water is 1000 kg/m$^3$.

**Solution.**

(*i*) *Volume flow rate* Q = VA

where Area $A = \frac{\pi d^2}{4}$

$$= \frac{\pi \times (75 \times 10^{-3})^2}{4} = 4.417 \times 10^{-3} \text{ m}^2$$

Volume flow rate $Q = 760 \times 10^{-3} \times 4.417 \times 10^{-3} = 3.357 \times 10^{-3}$ m$^3$/sec.

(*ii*) *Mass flow rate* W = ρQ

ρ is given as 1000 kg/m$^3$

Mass flow rate $W = 1000 \times 3.357 \times 10^{-3} = 3.357$ kg/sec.

**Problem 2.** Determine the volumetric flow of water in m$^3$/hr flowing in a pipe having a diameter of 40 mm through an orifice having a diameter of 20 mm. Manometer reading across the tapping is 15 cm of Hg. Assume correction factor = 1 and density of water is 1000 kg/m$^3$.

**Solution.** Diameter of pipe D = 40 mm

Diameter of orifice *d* = 20 mm

Manometer reading (differential pressure) = 15 cm of Hg.

Differential pressure is calculated in terms of water column as

$$h = (13.6 - 1) \times (15 \times 10) \text{ mm of water}$$

[density of mercury is 13.6 times that of water, and the manometer limbs are filled with water above mercury column.]

$$= 1890 \text{ mm of water.}$$

$$\beta = d/D = 20 \text{ mm}/40 \text{ mm} = 1/2$$

Velocity approach factor

$$M_{v.a} = \frac{1}{\sqrt{1-(d/D)^4}} = \frac{1}{\sqrt{1-(1/2)^4}} = 1.032$$

C*d* for *d*/D ratio is 0.5999 from the graph [BS : 1042 : 196]. Volumetric flow rate is calculated as follows :

$$Q = C_d M_{v.a} A_2 \cdot \sqrt{2gh} \text{ m}^3\text{/sec}$$

$$Q = 0.5999 \times 1.032 \times \pi/4\, (20 \times 10^{-3})^2 \cdot \sqrt{2 \times 9.81 \times 1890 \times 10^{-3}}$$

$$= 1.184 \times 10^{-3} \text{ m}^3\text{/sec} = 1.184 \times 10^{-3} \times 3600 = 4.262 \text{ m}^3\text{/hr}$$

**Problem 3.** Determine the nominal flow velocity $V_2$ at the orifice having a diameter of 20 mm kept in a pipe of 40 mm diameter. Reynolds number $R_a$ is $10^5$. Assume density of water = 1000 kg/m$^3$ and kinematic viscosity is $10^{-2}$ stokes. (cm$^2$/sec).

**Solution.** We know from equation 1.9

$$R_e = \rho V_1 D/\mu$$

This can be rewritten as

$$V_1 = R_e\,\mu/\rho D = R_e\,\nu/D \text{ [since } \mu = \rho\nu]$$

given : $\nu$ = Kinematic viscosity = $10^{-2}$ stokes. = $10^{-2}$ cm$^2$/sec = $10^{-6}$ m$^2$/sec

$$R_e = 10^5$$

$$D = 40 \times 10^{-3} \text{ m}$$

$$V_1 = R_e\,\nu/D = 10^5 \times 10^{-6}/(40 \times 10^{-3})$$

$$= 2.5 \text{ m/sec}$$

$$V_1A_1 = V_2A_2$$

$V_2$ = Nominal velocity at the orifice

$$= V_1 \times A_1/A_2 = 2.5 \times \frac{\pi/4\,(40 \times 10^{-3})^2}{\pi/4\,(20 \times 10^{-3})^2}$$

$$= 2.5 \times (4^2/2^2) = 2.5 \times (16/4) = 10.0 \text{ m/sec.}$$

**Problem 4.** For the above problem (2), calculate the pressure difference at the tappings. Assume corner tapping is the selected type. Assume $C_d = 0.61$

**Solution.** D = 40 mm

$d$ = 20 mm

From equation 1.4

$$V_2 = Cd\,\frac{\sqrt{2g(P_1 - P_2)/\rho}}{\sqrt{1-(A_2/A_1)^2}}$$

$$M_{v.a} = \frac{1}{(\sqrt{1-(A_2/A_1)^2})} = \frac{1}{\sqrt{1-(d/D)^4}} = \frac{1}{(\sqrt{1-((20\times 10^{-3}/40\times 10^{-3})^4})}$$

$$= \frac{1}{\sqrt{1-(1/2)^4}} = \frac{1}{\sqrt{1-0.0625}} = 1.0327.$$

$V_2$ = 10 m/sec [It is calculated in the problem (3)]

$$10 = 0.61 \times 1.0327 \times \sqrt{(2 \times 9.81 \times (P_1 - P_2)/1000}$$

$$\frac{\sqrt{2\times 9.81}}{\sqrt{1000}}\sqrt{P_1 - P_2} = \frac{10}{0.61 \times 1.0327}$$

$$\sqrt{0.01962\,\sqrt{P_1 - P_2}} = 15.87$$

$$0.14\,\sqrt{P_1 - P_2} = 15.87$$

$$\sqrt{P_1 - P_2} = 113.35$$

$$P_1 - P_2 = 12849.8 \text{ kg/m}^2 = 1.28 \text{ kg/cm}^2.$$

**Problem 5.** Determine the volume flow rate of water through a pipe of 150 mm diameter when measured by (*i*) an orifice plate of size 75 mm dia and (*ii*) Venturi tube of throat size 75 mm dia. The differential pressure recorded is 250 pa. Assume the density of water is 1000 kg/m$^3$.

**Solution.** Volume flow rate of water is calculated as follows.

$$Q = \frac{1}{\sqrt{1-(d/D)^4}} \times Cd \,.\, \frac{\pi d^2}{4} \times \sqrt{2gh}$$

where $h = P_1 - P_2/\rho$

(*a*) *For orifice plate :* $Cd = 0.6$

$$Q = \frac{1}{\sqrt{1-(1/2)^4}} \times 0.6 \times \frac{\pi(75 \times 10^{-3})^2}{4} \times \sqrt{(2 \times 9.81 \times 250)/1000}$$

$$= 1.032 \times 0.6 \times 4.417 \times 10^{-3} \times 2.214$$

$$= 0.006057 \text{ m}^3/\text{sec.} = 6.057 \text{ litres/sec.}$$

(*b*) *For venturi Tube :* $Cd = 0.99$

$$Q = 1.032 \times 0.99 \times 4.417 \times 10^{-3} \times 2.214$$

$$= 9.99 \times 10^{-3} \text{ m}^3/\text{sec.} = 9.99 \text{ litres/sec.}$$

**Problem 6.** A venturi tube of throat diameter 10 cm is placed in a pipe of diameter 20 cm to measure the volumetric flow. The volumetric flow rate through venturi tube is 0.02 m$^3$/sec. Water has the viscosity of $10^{-3}$ Pas. Determine the Reynolds number and the upstream to throat differential pressure developed.

**Solution.**

(*i*) *Reynolds number* $= \dfrac{\rho V d}{\mu}$

Volumetric flow rate $= 0.02$ m$^3$/sec.

Velocity = Volumetric flow/area $= \dfrac{0.02}{\pi/4(10 \times 10^{-2})^2}$

*i.e.,* $V = 2.546$ m/sec.

Now Reynolds number $R_e = \dfrac{1000 \times 2.546 \times (10 \times 10^{-2})}{10^{-3}} = 2.546 \times 10^5$.

(*ii*) *Volumetric flow rate :*

$$Q = M_{v.a}\, Z \,.\, a_2 \sqrt{2g(P_1 - P_2)/\rho} \qquad ...(1)$$

where $Cd = 0.98$

$Q = 0.02$ m$^3$/sec.

Assume $Z = 1$,

$$M_{v.a} = \frac{1}{\sqrt{1-(d/D)^4}} = \frac{1}{\sqrt{1-(10/20)^4}}$$

$$M_{v.a.} = \frac{1}{\sqrt{1-(1/2)^4}} = 1.032$$

$$a_2 = \frac{\pi(10 \times 10^{-2})}{4} = 7.85 \times 10^{-3}.$$

Substituting all the values in Equation (1),

$$0.02 = 1.032 \times 0.98 \times 7.85 \times 10^{-3} \times \sqrt{\frac{(2 \times 9.81 \times \Delta P)}{1000}}$$

$$0.02 = 7.939 \times 10^{-3} \sqrt{\frac{(2 \times 9.81 \times \Delta P)}{1000}}$$

$$\sqrt{\frac{(2 \times 9.81 \times \Delta P)}{1000}} = 2.52$$

$$0.14\sqrt{\Delta P} = 2.52$$

$$\sqrt{\Delta P} = 2.52/0.14 = 18$$

$$\Delta P = 324 \text{ kg/m}^2 = 0.0324 \text{ kg/cm}^2.$$

**Problem 7.** An incompressible fluid is flowing in a 300 mm pipe under a pressure head of 2 kg/cm$^2$. Calculate the fluid velocity and volumetric flow rate.

**Solution.** *Fluid velocity.*

$$V = \sqrt{2gh}$$

$$V = \sqrt{2 \times 9.8 \times (20)} \qquad [1 \text{ kg/cm}^2 = 10 \text{ metres water head}]$$

$$= 19.8 \text{ m/sec}^2.$$

*Volumetric flow rate.* Q = AV

where Area $A = \frac{\pi d^2}{4}$

$$d = (300 \times 10^{-3}) \text{ m}$$

$$A = \frac{\pi(300 \times 10^{-3})^2}{4} = 0.07 \text{ m}^2.$$

$$Q = 19.8 \text{ m/sec} \times 0.07 \text{ m}^2 = 1.38 \text{ m}^3/\text{sec}.$$

**Problem 8.** An incompressible fluid is flowing through an orifice plate with a flow coefficient of 0.6 causing a pressure drop of 400 mm of water column. Calculate the fluid velocity.

**Solution.** The fluid velocity measured by an orifice is given by an equation

$$V = C_d \sqrt{2gh}$$

where $C_d = 0.6$

$g = 9.8$ m/sec$^2$.

$h = (400 \times 10^{-3})$ m

$$V = 0.6 \sqrt{2 \times 9.8 \times 400 \times 10^{-3}} = 1.68 \text{ m/sec}.$$

**Problem 9.** A pitot tube with a coefficient of 0.98 is used to measure the velocity of water in a pipe. The differential pressure head is 900 mm. What is the velocity ?

**Solution.** $V = C_d \sqrt{2gh}$

where $C_d = 0.98$

$g = 9.8 \text{ m/sec}^2$

$h = (900 \times 10^{-3}) \text{ m}$

$$V = 0.98 \sqrt{2 \times 9.8 \times 900 \times 10^{-3}} = 4.11 \text{ m/sec.}$$

**Problem 10.** Determine the flow velocity necessary to produce a dip of 20 kPa from a pitot-static velocity measurement when used (*a*) in water (*b*) in air.

**Solution.** Assume density of water = 1000 kg/m$^3$ and Density of Air = 1.29 kg/m$^3$.

$$\text{Flow velocity} = V = \sqrt{2gh/\rho} = \sqrt{2\Delta P/\rho}$$

$$\Delta P = 20 \text{ kPa.}$$

(*i*) *When flowing fluid is water.*

$$V = \sqrt{2 \times 20 \times 10^3/1000} = 6.324 \text{ m/sec.}$$

(*ii*) *When air is flowing,*

$$V = \sqrt{2\Delta P/\rho} = \sqrt{2 \times 20 \times 10^3/1.29} = 176 \text{ m/sec.}$$

**Problem 11.** A pitot tube properly placed just in front of the submarine is connected to a manometer. The pressure difference in the manometer was found as 25 kN/m$^2$. Find the speed of submarine if the density of sea water is 1026 kg/m$^3$.

**Solution.** Flow velocity $= V = \sqrt{\dfrac{2\Delta P}{\rho}}$

$\Delta P = 25 \text{ kN/m}^2$

$\rho = 1026 \text{ kg/m}^3$

$$V = \frac{\sqrt{2 \times 25 \times 10^3}}{\sqrt{1026}} = 6.98 \text{ m/sec} = 25.128 \text{ km/hr.}$$

**Problem 12.** A pitot tube mounted on an aircraft is connected to a pressure gauge which reads a pressure of 12.5 kN/m$^2$. Determine the flying speed of the aircraft ? Density of air at that height can be taken as 1.290 kg/m$^3$.

**Solution.** Flying speed $= \sqrt{\dfrac{2\Delta P}{\rho}}$

$$= \sqrt{\frac{2 \times 12.5 \times 10^3}{1.290}} = 139.21 \text{ m/sec} = 501.16 \text{ km/hr.}$$

**Problem 13.** A rotameter uses a cylindrical float of 3.5 cm height, 3.5 cm dia and density of 3900 kg/m$^3$. The maximum inside diameter of the metering tube is 5 cm. Determine the maximum flow rate handling capacity of the rotameter if the fluid is water.

**Solution.** The volume of the float

$$V_f = \frac{\pi(3.5 \times 10^{-2})^3}{4} = 3.36 \times 10^{-5} \text{ m}^3$$

Assume $Cd = 0.6$ (For water)

Dia of the float $D_f = (3.5 \times 10^{-2})$ m

Inside diameter of the Pipe

$$D_p = (5 \times 10^{-2}) \text{ m}$$

Volume of the float $V_f = 3.36 \times 10^{-5}$ m$^3$

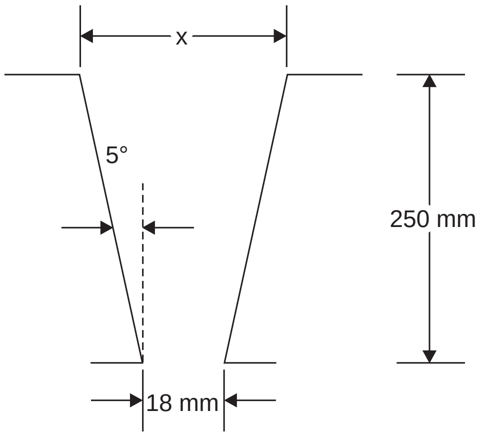
Volumetric flow
$$Q = Cd \cdot \frac{D_p^2 - D_f^2}{D_f} \sqrt{\frac{\pi g V_f (\rho_f - \rho)}{2\rho}}$$

$$= 0.6 \times \left[\frac{0.05^2 - 0.035^2}{0.035}\right] \frac{\sqrt{\pi \times 9.8 \times 3.36 \times 10^{-5} \times (3.9 \times 10^3 - 1 \times 10^3)}}{\sqrt{2 \times (1 \times 10^3)}}$$

$$= 0.6 \times 0.03642 \times \sqrt{1.499 \times 10^{-3}} = 0.6 \times 0.03642 \times 0.03872$$

$$= 8.4631 \times 10^{-4} \text{ m}^3/\text{sec.}$$

**Problem 14.** Consider a rotameter float of volume of 520 mm$^3$ with an included angle taper of 5°, with an effective diameter of 15 mm and a vertical range of movement of 250 mm and is made from aluminium of relative density 2.7. If the internal diameter of the measuring tube at the bottom is 18 mm. Determine the range of flow if paraffin is used as a process fluid which has a relative density of 0.8.




**Solution.** Given $V_f = [520 \times 10^{-9}]$ m$^3$

$D_f = 15$ mm

$$A_f = \frac{\pi(15 \times 10^{-3})^2}{4}$$

$$= 1.7671 \times 10^{-6} \text{ m}^2$$

$Cd = 1$

From the figure $x = 18 + 2 \times 250 \times \tan 5$

$= 61.7$ mm.

**Case 1.** When float is at the bottom, the flow through the rotameter is minimum [$D_p$ = 18 mm]

$$Q_{min} = \frac{D_p^2 - D_f^2}{D_f} \sqrt{\frac{\pi g V_f (\rho_f - \rho)}{2\rho}}$$

$$= \left[\frac{(18 \times 10^{-3})^2 - (15 \times 10^{-3})^2}{15 \times 10^{-3}}\right] \sqrt{\frac{\pi \times 9.8 \times 520 \times 10^{-9} \times (2.7 - 0.8)}{2 \times 0.8}}$$

$$= 6.6 \times 10^{-3} \times \sqrt{1.903 \times 10^{-5}} = 6.6 \times 10^{-3} \times 4.362 \times 10^{-3}$$

$$= 2.879 \times 10^{-5} \text{ m}^3/\text{sec.}$$

**Case 2.** When float is at the top, the flow through the rotameter is maximum [$D_p$ = 61.7 mm]

$$Q_{max} = \frac{(61.7 \times 10^{-3})^2 - (15 \times 10^{-3})^2}{15 \times 10^{-3}} \sqrt{\frac{\pi \times 9.81 \times 520 \times 10^{-9} \times (1.9/0.8)}{2}}$$

$$= 0.2387 \times 4.362 \times 10^{-3} = 104.1 \times 10^{-5} \text{ m}^3/\text{sec.}$$

**Problem 15.** A coal conveyor system moves at a speed of 328 m/min. A weighing platform is 16 m in length and a particular weighing shows a reading of 165 kg. Find the coal delivery in kg/hr.

**Solution.** The flow rate can be calculated as

$$Q = \frac{WR}{L}$$

where Q = Flow rate.

W = weight of material on section of length.

R = Conveyor speed m/min.

L = Length of weighing platform in m.

$$Q = \frac{(165 \text{ kg}) \times (328 \text{ m/min})}{16 \text{ m}}$$

$$= 3382.50 \text{ kg/min} = 56.4 \text{ kg/hour.}$$

**Problem 16.** Given a beat frequency ($\Delta f$) of 100 cps for an ultrasonic flowmeter, the angle ($\theta$) between the transmitters and receivers is 45° and the sound path ($d$) is 300 mm. Calculate the fluid velocity in m/sec. [Assume the ultrasonic transmitter is of single transducer assembly type].

**Solution.** Fluid velocity is calculated by

$$V = \frac{\Delta f \, . \, d}{2 \cos \theta}$$

where $\Delta f$ = 100 cps

$d$ = 300 m

$\theta$ = 45°

$$V = \frac{100 \times (300 \times 10^{-3})}{2 \cos 45^\circ} = \frac{30}{2 \times 0.707} = 21.2 \text{ m/sec.}$$

**Problem 17.** Determine the volume flow rate in litres/min in an oval gear type flow meter. The volume trapped between the gears and the casting is 120 CC and the speed of the rotation is 150 rpm.

**Solution.** We know that in an oval gear type flow meter, the volume flow rate is 4 times the speed of rotation, of the volume trapped between the gear and the casting.

Volume flow rate Q = 4 × 150 × 120 = 72000 $\text{cm}^3$/min = 72 litres/min.

**Problem 18.** Calculate the induced emf in an electromagnetic flow meter due to the flow of a conductive fluid in a pipe with inner diameter of 2.75 cm. The flux density B = 6 mV. sec/cm$^2$ and volume flow rate Q = 2500 cm$^3$/min.

**Solution.** Quantity Flow rate Q = 2500 cm$^3$/min

$$\text{Area} = \frac{\pi d^2}{4} = \frac{\pi}{4}\ (2.75)^2 = 5.94\ \text{cm}^2.$$

$$\text{Velocity} = \frac{2500}{60 \times 5.94} = 7.01\ \text{cm/sec}.$$

Flux density B = 6 mV sec/cm$^2$

$$= \frac{6 \times 10^{-3}\ \text{V sec}}{(10^{-2})^2\ \text{m}^2} = 60\ \text{V sec/m}^2 = 60\ \text{Weber/m}^2.$$

$$\text{Induced emf } e = Blv = 60 \times (2.75 \times 10^{-2}) \times (7.01 \times 10^{-2})$$

$$= 0.1156\ \text{V} = 115.6\ \text{mV}.$$

**Problem 19.** Determine the velocity of flow in an electromagnetic flow meter for the following conditions. The flux density in the liquid has an average value of 0.08 Weber/m$^2$. The diameter of the pipe is 10 cm. The induced voltage of the electromagnetic flow meter is recorded as 0.2 mV.

**Solution.** $e = \text{B}\ lv$

$$v = \frac{e}{\text{B}l} = \frac{0.2 \times 10^{-3}}{0.08 \times (10 \times 10^{-2})}$$

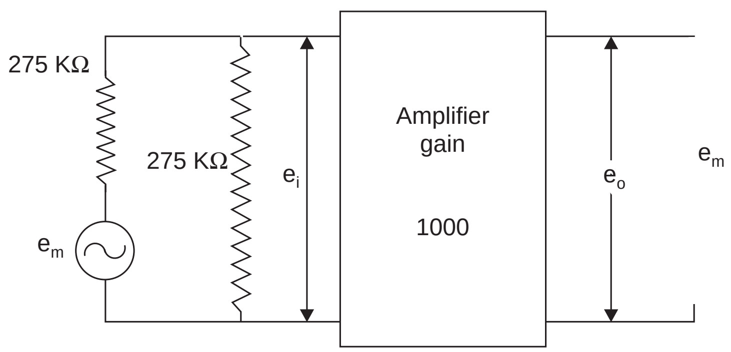
$$= 0.025\ \text{m/sec} = 2.50\ \text{cm/sec}.$$

**Problem 20.** Consider an electromagnetic flow meter which is used to measure volumetric flow of a process fluid in a pipe of 60 mm dia. The velocity profile is symmetrical and can be assumed uniform. The flux density in the liquid is 0.1 Wb/m$^2$. The output from the flow meter is given to an amplifier of gain 1000 and impedance between the electrodes is 275 KΩ. The input impedance of the amplifier is 275 KΩ. Find the average velocity of the liquid when the P-P voltage at the amplifier output is 0.3 V.

**Solution.** Diameter of the pipe = 60 mm.

Flux density = 0.1 Weber/m$^2$.

Amplifier gain = 1000.

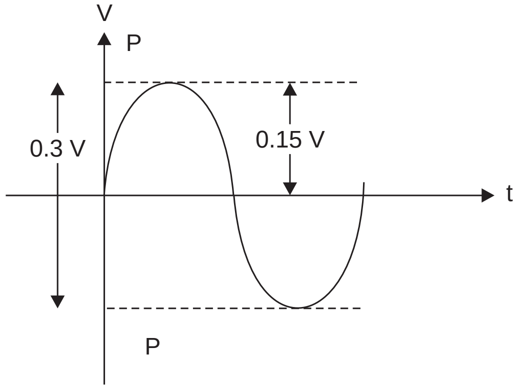


P-P Amplifier output = 0.3 V.

Peak value = 0.15 V.

Input to the Amplifier = $0.15 \times 10^{-3}$ V.

(Peak value).




From the above circuit diagram.

$$e_i = \frac{275}{275 + 275} e_m$$

$$[275 + 275]\, e_i = 275\, e_m$$

$$2e_i = \mathbf{e_m}$$

$$\mathbf{e_m} = 2 \times 0.15 = 0.3 \times 10^{-3} \text{ V.}$$

We know that, $e_m = Blv$.

Velocity of flow $v = e_m/Bl$

$$= \frac{0.3 \times 10^{-3}}{0.1 \times 60 \times 10^{-3}} = 0.05 \text{ m/sec} = 5 \text{ cm/sec.}$$

## 1.10 Questions and Problems

1. List the different units of flow.
2. Define mass flow rate.
3. What is meant by variable area flow meter ?
4. Water is pumped through a 150 mm diameter pipe with a flow velocity of 3.5 m/sec. Find the volume flow rate and the weight flow rate. The density of water is 1000 kg/$m^3$.
5. An incompressible fluid is flowing through an orifice plate with a flow coefficient of 0.5, causing a pressure drop of 500 mm. Calculate the fluid velocity.
6. Explain the flow measurement by orifice plate with the help of a sketch giving the installation details.
7. Does the venacontracta position change in fluid flow line with change in fluid flow rate ?
8. When is a Venturi tube preferable to orifice plate ?
9. A pitot tube with coefficient of 0.93 is used to measure the velocity of air in a pipe. The measured differential pressure is 300 mm. What is the velocity of air in the pipe ?
10. Explain the advantages and disadvantages of the three main types of orifice plates.
11. Discuss the basic principle used in positive-displacement flow meters to measure fluid flow.
12. An incompressible fluid is flowing in a 100 mm pipe under a pressure head of 1.5 kg/$cm^2$. Calculate the fluid velocity and volume flow rate.
13. Explain in detail the operation of rotary-vane, oval-gear and nutating disk PD flow meters.
14. What is meant by inferential flow meters ?

15. What are the types of inferential flow meters ?
16. Explain about target flow meters.
17. What is the principle of turbine flow meter ?
18. Does the operation of the turbine flow meter depend on liquid characteristics ?
19. Will you recommend DC supply to the electromagnet of a magnetic flow meter carrying mercury ?
20. Which flow meters are preferable for the measurement of flow of corrosive liquids ?
21. What is the concept of cross-correlation flow meter ?
22. How will you measure the flow rate of solids ?
23. An incompressible fluid is flowing in a 300 mm pipe under a pressure head of 2.5 kg/$cm^2$. Calculate the fluid velocity and volume flow rate.
24. How will you measure the mass flow rate ?
25. What are the types of mass flow meters ?
26. State the features of 'coriolis' mass flow meters.
27. What is 'Vortex' ?
28. What is a flow switch ?
29. What are the types of flow switches ?
30. What is the principle of hot-wire anemometers ?
31. Explain the two types of hot wire anemometers.
32. Explain the types of mechanical anemometers.
33. Explain the principle of thermal mass flow meters.
34. Explain the excitation schemes of an electro magnetic flow meter.
35. Explain the principle of operations of an electromagnetic flow meter. Discuss its merits.
36. In an ultrasonic flow meter, the beat frequency is 805 cps, the angle (θ) between the transmitters and receivers is 45°, and the sound path is 125 mm. Calculate the fluid velocity in m/sec.
37. Which type of flow meter can be used to calibrate other flow meters ?
38. State the types of calibration methods available for gas flow measurement.
39. Write short notes on flow regulators.
40. Briefly explain about the selection of a flow meter.