$$q_{v1} = \frac{306}{273} \times \frac{(273 + 26.7)}{0.95} = 353.6 \text{ m}^3/\text{h}$$

$$P_0 = \frac{2.78 \times 10^{-4}}{0.8} \frac{1.31}{1.31 - 1} \times 353.6 \times 0.95 \times 101.325 \left((4.01)^{\frac{0.31}{1.31}} - 1 \right)$$

$$= 19.45 \text{ kW}$$

If power loss in allied piping and intercoolers is neglected, then total power required for three stages,

$$P_0' = 3 \times 19.45 = 58.35 \text{ kW}$$

(b) Discharge temperature after first stage

$$T_2 = T_1 \left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}}$$

$$T_2 = (273 + 26.7)(4.01)^{(0.31/1.31)}$$
$$T_2 = 416.3 \text{ K}, t_2 = 143.3°\text{C}$$

or

for $k = 1.31$ and $r = 4.01$, from Fig. 5.9:
$d = 0.54$, $(X_G/X) = 0.8$

$$X = r^{\frac{0.395}{1.395}} - 1 = 4.01^{\left(\frac{0.395}{1.395}\right)} - 1 = 0.4818$$

$$X_G = 0.8 \times 0.4818 = 0.3854$$

Power required for each stage

$$P_0 = 6.37 \times 10^{-4} \frac{q_{v1} p_1}{\eta} \frac{X_G}{d} \tag{5.27}$$

$$P_0 = \frac{6.37 \times 10^{-4} \times 353.6 \times 96.2587}{0.8} \times \frac{0.3854}{0.54} = 19.34 \text{ kW}$$

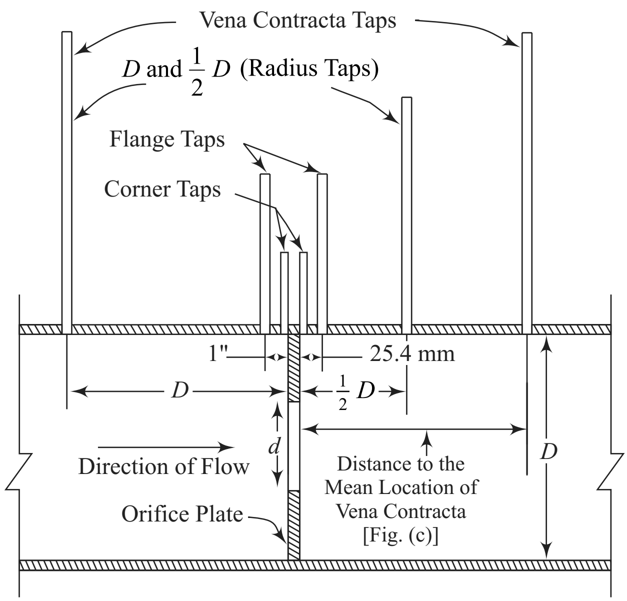
Total power required $P_0' = 3 \times 19.34 = 58.03$ kW
(Neglecting pressure loss in the intercoolers and allied piping)

5.6 FLOW METERS

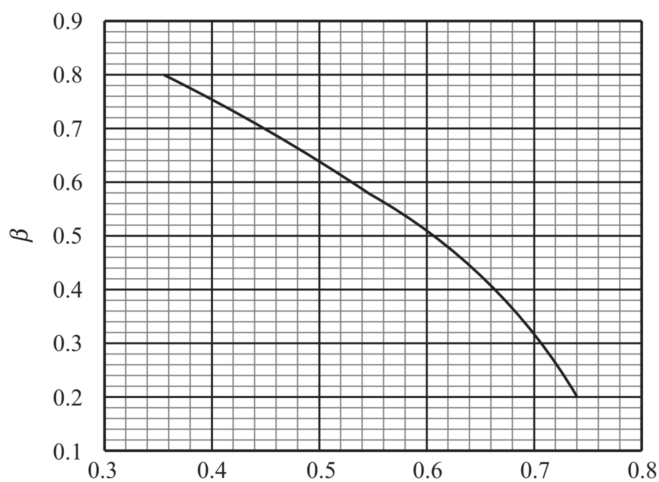
A variety of flow meters are in use in chemical process industry. One category is the traditional differential pressure (DP) type volumetric flow meters. In many applications, the volumetric flow rate is of direct interest to the user. Because of its accuracy, simplicity and relatively lower cost, these flow meters are popular in the chemical industry. By multiplying the flow rate with the actual density, mass flow rate can be obtained. Pitot tube, orifice meter, venturi meter and flow nozzles fall under this category. Among these, orifice meter is by far the most popular in the industry. Figure 5.10 shows these meters schematically.

Less commonly used flow meter is vortex meter which works on Von Karman effect. Flowing fluid separates on two sides of shedder bar face. Vortices form behind the face and cause alternating differential pressures (DP) around the back of the shedder.

The frequency of the alternating vortex development is linearly proportional to the volumetric flow rate. Although vortex meters are as reliable and as accurate as other DP instruments, they can be used for only clean liquids and are recommended for turbulent flows.

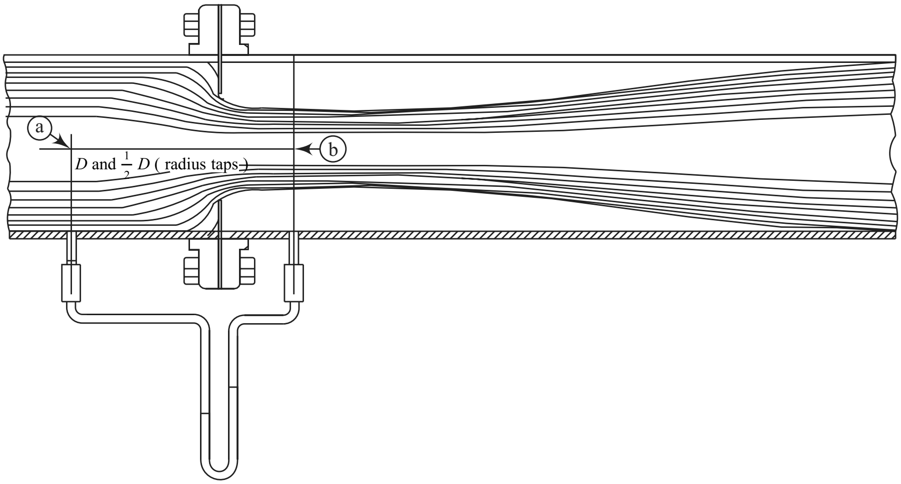


(a) Various Tap Locations for Orifice Meter



Pipe Diameters from Inlet Face of Orifice Plate
(*Extracted from the ASME Flow Meter Computation Handbook, 1961*)

(b)



Orifice Meter with Vena Contracta Formation

(c)

Fig. 5.10 *Orifice Meter*

Another popular category is of variable area flow meters which are also known as rotameters. Figure 5.11 shows two different types of rotameters. While DP type instruments can be installed in horizontal position, rotameters are installed in vertical position. Bypass rotameters are installed in horizontal position which is a combination of an orifice and a rotameter. Bypass rotameters are installed on larger size pipelines and occupy quite less space. Near linear scale of the meter is an advantage over logarithmic scale for the DP meters. However, rotameters with glass tubes are relatively less accurate and are mainly used for low pressure applications.

Disadvantage of low pressure applications due to glass tubes has led to the development of magnetic rotameters in which a magnetic float is used in a metallic tapered tube and its accurate position is monitored outside the tube. Float's movement is calibrated on a dial-type indicator. Both DP type and magnetic rotameter can be connected to a microprocessor-based control unit for totalizing and/or controlling purpose.

Positive displacement-type flow meters incorporate a pair of gears or a turbine which rotate on their axes and the revolutions are measured. Since volume displaced per revolution is nearly constant, volumetric flow is calculated by multiplying two parameters. Traditional water meters are of gear type. Turbine flow meters are available for number of liquids such as ammonia, chlorine, etc., which flow under relatively high pressure. These instruments are sufficiently accurate and are used for custody transfer.

Weirs are popularly used for volumetric flow measurements in open canals and alike situations. Figure 5.12 shows different types of weirs in use.

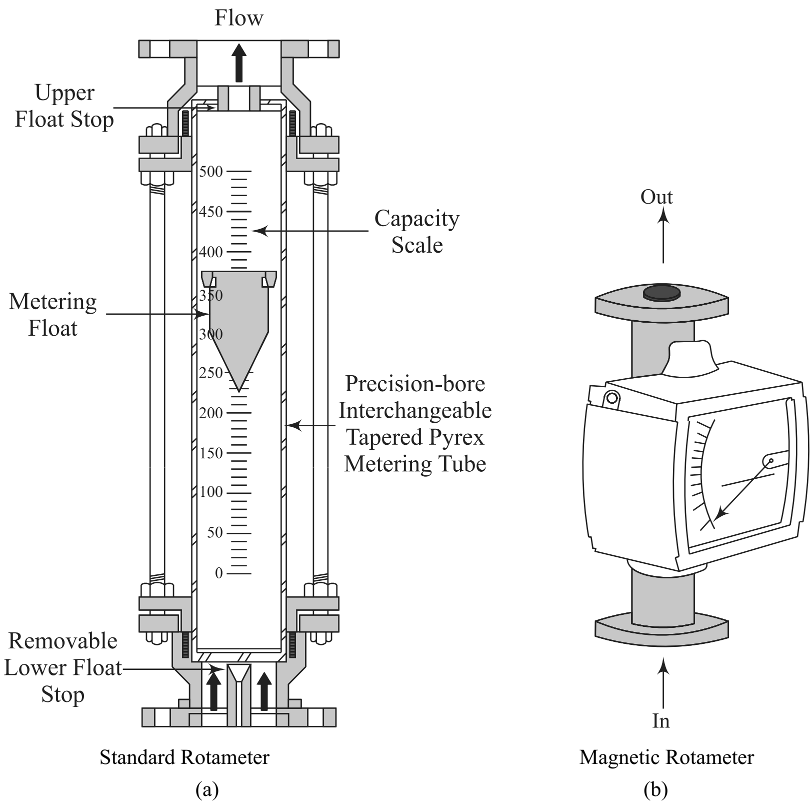


Fig. 5.11 *Rotameters*

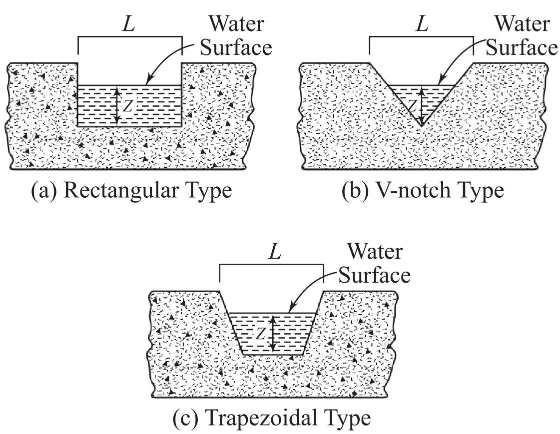


Fig. 5.12 *Flow Measurement with Weirs*

Another category relates to ultrasonic flow meters. Its underlying principle is measurement of the effect a flowing fluid has on an ultrasound signal either transmitted through or reflected from the fluid. These instruments are largely of clamp-on designs and offer simplicity of installation. These meters suffer from a reputation for unreliability and poor long-term stability, compared with DP type meters. However, newer designs are being developed for high pressure and temperature fluids, including gases. Designs are available when a single instrument can be clamped on a range (though limited) of pipes and volumetric flows can be checked periodically. This type of meter is quite handy to a process engineer in checking plant performance from time to time.

Electromagnetic flow meters (also known as magmeters) work on Faraday's law of conductance which states that when a conductive fluid flows through a magnetic field, generated perpendicular to the flow, the voltage induced in the fluid is linearly proportional to the volumetric flow rate. Thus, this type of instrument operates only with electrically conductive liquid. Non-invasive nature of ultrasonic flow meter is also the feature of magmeter. Both permit unobstructed flow through the measuring element. Both are clamp on meters whose transducers are strapped to the pipeline. Unlike ultrasonic meters, magmeters have a reputation of accuracy.

True mass flow meter based on Coriolis principle was introduced in 1977 by Mirco Motion, Inc., USA, a division of Emerson Process Management. The Coriolis principle, discovered by Gustave Coriolis in 1935 states that fluid flowing through a tube, vibrating at its natural frequency, generates a force that slightly distorts the tube. This extremely small distortion, picked up by sensors, is directly proportional to the mass flow rate (Newton's second law of motion) and is independent of any other property of the fluid; say pressure, temperature, density or viscosity. Figure 5.13 schematically represents the mass flow meter.

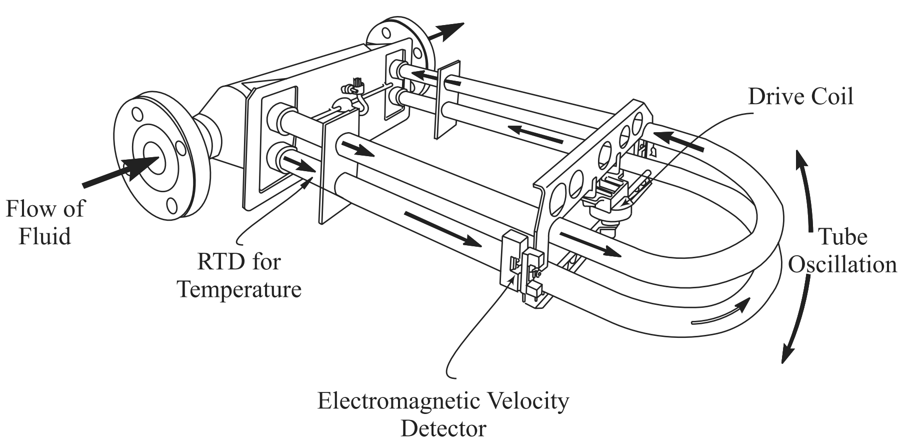
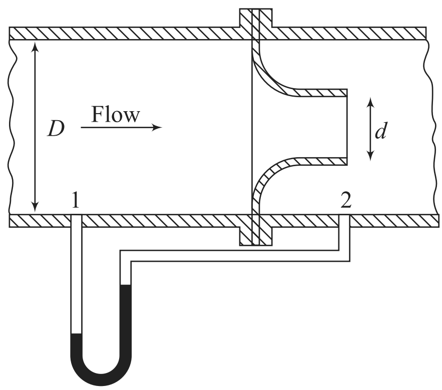


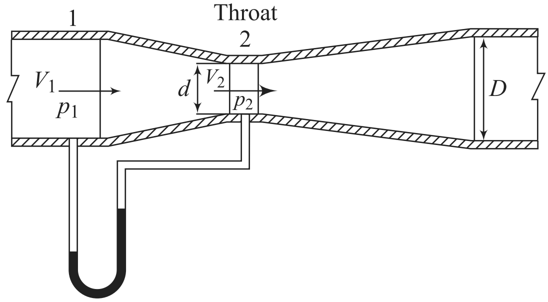
Fig. 5.13 *Coriolis Mass Flow Meter (Courtesy: Micro Motion, Inc., USA)*

In a single mass flow meter, four parameters of the fluid can be measured at a time; mass flow, volumetric flow, temperature, and density. This instrument offers high accuracy and can be used for any fluid; clean or dirty, transparent or opaque, conductive or non-conductive. Originally developed instrument required extra space for installation but recently developed meter has a straight tube configuration. Among different types of flow meters, Coriolis device is the costliest.

In the forthcoming sections, process designs of orifice meter and rotameter are discussed. Reader is advised to refer standard handbooks on instrumentation/flow meters for design of other flow meters.



Flow Nozzle with Differential Gauge
(a)



(b) Venturi Meter

Fig. 5.14

5.7 PROCESS DESIGN OF ORIFICE METER

Orifice meter is a widely used flow meter in chemical industry, compared to venturi meter and rotameter.

Advantages of orifice meter are:

1. Fixed cost is less
2. Easy to fabricate and install
3. Occupies less space as compared to the venturi meter
4. Provides more flexibility. Orifice plate can be easily replaced.

Disadvantages of orifice meter is higher power consumption and hence operating cost of orifice meter is higher than the same of venturi meter and of rotameter.

In orifice meter, as shown in Fig. 5.10, a square edged or sharp edged orifice plate is mounted between two flanges at the flanged joint. When fluid flows through the orifice it forms free flowing jet. This free flowing jet first contracts and then expands. Minimum flow area achieved by free flowing jet is known as Vena Contracta.
Mass flow rate through orifice is given by the following equation:

$$\dot{m} = C_o Y A_o \sqrt{\frac{2g_c(p_1 - p_2)\rho}{1-\beta^4}} \tag{5.30}$$

where, $\dot{m}$ = Mass flow rate of fluid, kg/s

A_0 = Area of orifice = $(\pi/4)d_0^2$, m^2

p_1, p_2 = Pressure at upstream and downstream static pressure taps, respectively, Pa

ρ = Density of fluid, kg/m^3

$$\beta = \frac{\text{Diameter of orifice}}{\text{Inside diameter of pipe}}$$

Y = Expansion factor
= 1 for liquids
= $1 - [((1 - r)/k)(0.41 + 0.35\,\beta^4)]$ for gases (5.31)

where, $r = \dfrac{p_2}{p_1}$, ratio of downstream to upstream pressure

$k = \dfrac{C_p}{C_v}$, specific heat ratio

C_o = Coefficient of orifice = $f(Re_o, \beta$, Location of taps)

where, Re_o = Reynold's number for the fluid flowing through orifice

$$Re_o = \frac{d_o u_o \rho}{\mu} = \frac{4\dot{m}}{\pi d_o \mu} \tag{5.32}$$

where, u_o = Velocity of fluid through orifice, m/s

μ = Viscosity of fluid, kg/(m · s)

Equation of orifice meter (Eq. 5.30) is empirical in nature and it requires experimental support.

In addition to Re_o and β, C_o also depends on the location of pressure taps. Location of pressure taps on upstream side and down stream side are also standardized as discussed in Fig. 5.10 (a).

There are total five standard locations of pressure taps:

1. **Corner taps:** Static holes made in upstream and downstream flange. They are very close to the orifice plate. With corner taps, it is possible to drill both static holes in the orifice plate itself. Then entire orifice meter can be easily inserted in any flanged joint without drilling the holes in pipe or flanges.
2. **Flange taps:** Static holes made at a distance 25.4 mm on upstream side and 25.4 mm on downstream side.

3. **Radius taps:** Static holes located at a distance one pipe diameter on upstream side and 1/2 pipe diameter on downstream side. Radius taps are the best from practical standpoint of view as it gives reasonably good pressure difference, compared to other taps except vena contracta taps. Higher pressure difference means more accurate measurement of flow rate.
4. **Vena contracta taps:** Upstream static hole is 1/2 to 2 times pipe diameter from the plate. Downstream tap is located at the position of minimum pressure. Vena contracta taps give the maximum pressure difference for a given flow rate. But it is not suitable, if orifice size is changed from time to time.
5. **Pipe taps:** Static holes are located at 2.5 times pipe diameter upstream side and 8 times pipe diameter on down stream side. This means fluid is flowing normally on both sides without being affected by turbulence, created by the orifice plate.

   For $Re_o > 30\,000$,

   C_o = Between 0.595 to 0.62 for vena contracta taps

   C_o = Between 0.595 to 0.8 for radius taps

   C_o = 0.62 for corner taps

   Relation between discharge coefficient C_o, β and Re_D is given by Stolz equation (ISO: 5167).

   $$C_o = 0.5959 + 0.0312\,\beta^{2.1} - 0.184\,\beta^8 + 0.0029\,\beta^{2.5}\,(10^6/Re_D)^{0.75} + 0.09\,L_1\,\beta^4\,(1-\beta^4)^{-1} - 0.0337\,L_2\,\beta^3 \tag{5.33}$$

   where, Re_D = Reynolds number based on internal diameter of pipe D

   $$L_1 = \left(\frac{l_1}{D}\right), \quad L_2 = \left(\frac{l_2}{d_o}\right)$$

   where, d_o = diameter of orifice

   $\beta = d_o/D$

   l_1 = Distance of the upstream tapping from the upstream face of orifice plate, mm

   l_2 = Distance of the downstream tapping from the downstream face of the orifice plate, mm

Example 5.20 Design an orifice meter based on the following data:

Name of fluid = water

Flow rate = 100 000 kg/h

Inside diameter of pipe = 154 mm (6 in, SCH-40 pipe)

Operating temperature = 32°C

Density of water at 32°C = 995.026 kg/m^3

Viscosity of water at 32°C = 0.765 mPa · s or cP

Manometer fluid = Mercury

Density of Mercury at 32°C = 13 516.47 kg/m^3

Solution

Inside diameter of pipe D = 154 mm

Let $\beta = 0.5$, i.e., $d_o/D = 0.5$

Diameter of orifice, $d_o = 77$ mm

Re_D = Reynolds number based on inside diameter of pipe

$$= \frac{4\dot{m}}{\pi D \mu} = \frac{4 \times (100\,000/3600)}{\pi \times 0.154 \times 0.765 \times 10^{-3}}$$

$$= 300\,210.2$$

Use square edged circular orifice plate with radius taps.

Radius taps are best from practical stand point. In radius taps, downstream tap is located approximately at the mean location of vena contracta (1/2 times pipe diameter) and also upstream tap is sufficiently far so that it is not affected by distortion of flow in the vicinity of orifice.

Based on Stolz's equation,

$$C_o = 0.5959 + 0.0312\beta^{2.1} - 0.184\beta^8 + 0.0029\,\beta^{2.5}\left(\frac{10^6}{Re_D}\right)^{0.75} + 0.09L_1\beta^4(1-\beta^4)^{-1} - 0.0337\,L_2\beta^3 \tag{5.33}$$

$$L_1 = \frac{l_1}{D} = 1,\ L_2 = \frac{l_2}{d_o} = 1$$

$$C_o = 0.5959 + 7.2776 \times 10^{-3} - 7.1875 \times 10^{-4} + 1.264 \times 10^{-3} + 6 \times 10^{-3} - 4.2125 \times 10^{-3}$$

$$= 0.6055$$

Mass flow rate of water

$$\dot{m} = C_o Y A_o \sqrt{\frac{2g_c \Delta p \rho}{1-\beta^4}} \tag{5.30}$$

Y = expansion factor for liquid = 1

$$\frac{100\,000}{3600} = 0.6055 \times 1 \times \frac{\pi}{4}(0.077)^2 \times \sqrt{\frac{2 \times 1 \times \Delta p \times 995.026}{1-0.5^4}}$$

$$\Delta p = 45\,722.597 \text{ Pa} \equiv 45.722 \text{ kPa} \equiv 4.661 \text{ m WC}$$

$$\Delta p = R_m \frac{g}{g_C}(\rho_m - \rho_f)$$

$$45\,722.597 = R_m \times \frac{9.81}{1}(13\,516.47 - 995.026)$$

R_m = Manometer reading = 0.3722 m Hg

$\equiv$ 372.2 mm Hg

In actual industrial practice, DP transmitter is used. Select the transmitter with 550 mm WC range so that the normal reading is at about 85% of the range.

Similarly, one can find different values of R_m for the different variation in flow rate or in other words calibration of orifice meter can be carried out.

Example 5.21 Design an orifice meter based on the following data:
Name of fluid = Chlorine gas
Flow rate = 1500 Nm^3/h
Operating pressure = 1.2 atm a
Operating temperature = 30°C
Viscosity of chlorine gas at 30°C = 0.0145 mPa · s or cP
Inside diameter of pipe = 154 mm (6 in. SCH-40)
Specific heat ratio for Cl_2 gas, $k = 1.355$

Solution

Let $\beta = 0.5$

$$\frac{d_o}{D} = 0.5 \quad \text{or} \quad d_o = 77 \text{ mm}$$

$$Re_D = \frac{4\dot{m}}{\pi D \mu}$$

Density of Cl_2 gas at normal condition

$$\rho = \frac{1 \times 71}{(273 + 25)} \times \frac{273}{1 \times 22.414} = 2.902 \text{ kg/m}^3$$

$$\dot{m} = 1500 \times 2.902 = 4353 \text{ kg/h}$$

$$Re_D = \frac{4 \times (4353/3600)}{\pi \times 0.154 \times 0.0145 \times 10^{-3}}$$
$$= 689\,457.6$$

If corner taps are made then $l_1 = l_2 = 0$
Coefficient of orifice meter can be determined by Stolz's equation.

$$C_o = 0.5959 + 0.0312\,\beta^{2.1} - 0.184\,\beta^8 + 0.0029\,\beta^{2.5}\left(\frac{10^6}{Re_D}\right)^{0.75}$$
$$+ 0.09 L_1 \beta^4 (1 - \beta^4)^{-1} - 0.0337 L_2 \beta^3 \quad (5.33)$$
$$= 0.5959 + 7.2776 \times 10^{-3} - 7.1875 \times 10^{-4} + 6.7755 \times 10^{-4}$$
$$= 0.6031$$

Expansion factor

$$Y = 1 - [((1 - r)/k)(0.41 + 0.35\beta^4)]$$
$$= 1 - [((1 - r)/1.355) \times 0.4319]$$

For the first trial calculation let $r = 0.8$, $Y = 0.9362$
Mass flow rate of chlorine gas

$$\dot{m} = C_o Y \frac{\pi}{4} d_o^2 \sqrt{\frac{2 g_c \Delta p \rho}{1 - \beta^4}} \quad (5.30)$$

Density of chlorine gas at operating condition:

$$\rho = \frac{1.2 \times 71}{(273 + 30)} \times \frac{273}{1 \times 22.414} = 3.425 \text{ kg/m}^3$$

$$\frac{4353}{3600} = 0.6031 \times 0.9362 \times \frac{\pi}{4}(0.077)^2 \times \sqrt{\frac{2 \times 1 \times \Delta p \times 3.425}{1 - 0.5^4}}$$

$$\Delta p = 28\,946.4 \text{ Pa}$$

$$\equiv 28.946 \text{ kPa}$$

$$p_1 = 1.2 \text{ atm}, p_2 = p_1 - \Delta p = 1.2 \times 101.325 - 28.946$$

$$p_2 = 92.644 \text{ kPa}$$

$$r = \frac{p_2}{p_1} = \frac{92.644}{121.59} = 0.762, \quad Y = 0.9241$$

$$\Delta p \propto \frac{1}{Y^2} \quad \text{or} \quad \Delta p_1 Y_1^2 = \Delta p_2 Y_2^2$$

$$\Delta p_2 = 28.946 \times \left(\frac{0.9362}{0.9241}\right)^2 = 29.7 \text{ kPa}$$

$$r = \frac{(121.59 - 29.7)}{121.59} = 0.7557 \equiv 0.762 \text{ (close enough to the previous value of } r\text{)}$$

$$\Delta p_2 = 29.7 \text{ kPa} \equiv 3.028 \text{ m WC (final)}$$

Similarly, for the different variation in the flow rate Δp can be determined. In this case also, a DP transmitter having 3500 mm WC range can be selected. Normal reading will be at about 87% of the range.

5.8 PROCESS DESIGN OF ROTAMETER

Rotameter is used for the flow measurement of liquids and gases. It is a variable area flow meter in which pressure drop is nearly constant and the area through which the fluid flows varies with the flow rate. It consists of tapered tube with the smallest diameter at the bottom. The tube contains a freely moving float which rests on a stop at the base of the tube. When the fluid is flowing the float rises until its weight is balanced by the upthrust of the fluid, its position then indicates the rate of flow. Float is **not** floating but is completely submerged in the fluid and its density is greater than the density of fluid. The tube is marked in divisions and the reading of the meter is obtained from the scale reading at the reading edge of the float which is taken at the largest cross section of the float. It is always mounted in the perfect vertical position. Rotameters are designed to measure the flow rate of fluid in certain range like 5 m^3/h to 50 m^3/h, 10 m^3/h to 100 m^3/h, 3 Lpm to 30 Lpm, etc.

For a linearly tapered tube with a diameter at the bottom about the float diameter, flow is almost a linear function of the height or position of float. As a tube material glass is the first choice. For high temperatures or pressures or for other conditions where glass is impracticable, metal tubes are used. In this case since, in metal tube, the float is invisible, means must be provided for either indicating or transmitting the meter reading.

Mass flow rate through rotameter is given by the equation

$$q_m = C_D A_2 \sqrt{\frac{2gV_f(\rho_f - \rho)\rho}{A_f[1 - (A_2/A_1)^2]}} \tag{5.34}$$