Lecture NO(14)

Flow Measurement

(14.1) Introduction

It is important to be able to measure and control the amount of material entering and leaving a chemical and other processing plants. Since many of the materials are in the form of fluids, they are flowing in pipes or conduits. Many different types of devices are used to measure the flow of fluids. The flow of fluids is most commonly measured using *head flow meters*. The operation of these flow meters is based on the Bernoulli's equation.

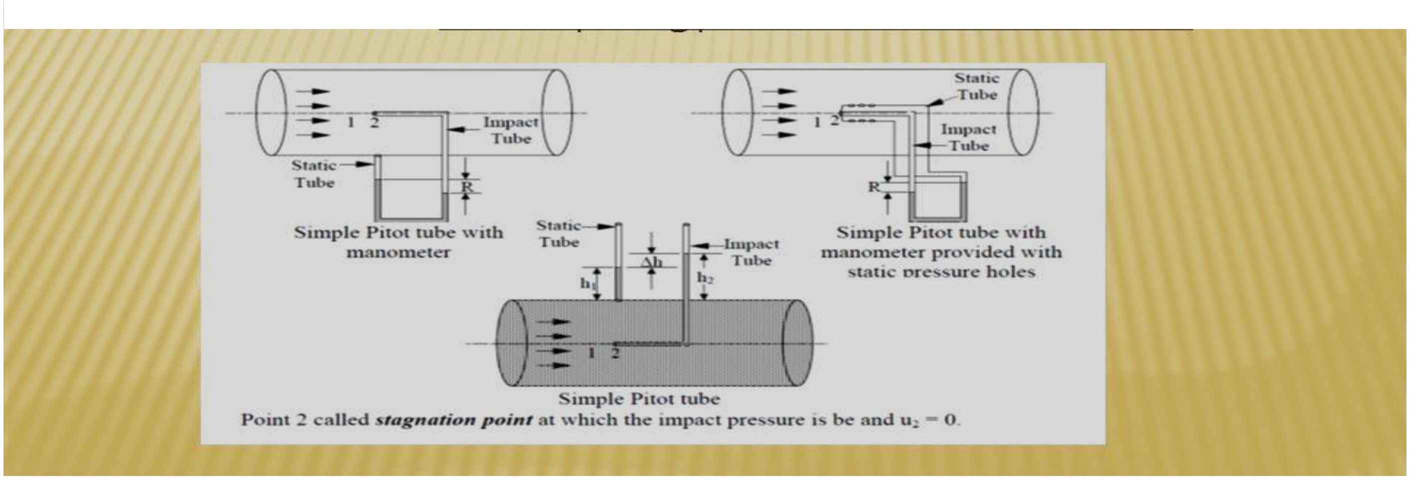
A construction in the flow path is used to increase in the lines flow velocity. This is accompanied by a decrease in pressure intensity or head and since *the resultant pressure drop is a function of the flow rate of fluid*, the latter can be evaluated.

(14.2) Flow Measurement Apparatus

Head flow meters include orifice, venture meter, flow nozzles, Pitot tubes, and wiers. They consist of primary element, which causes the pressure or head loss and a secondary element, which measures it.

(14.2.1) Pitot Tube

The Pitot tube is used to measure *the local velocity* at a given point in the flow stream and not the average velocity in the pipe or conduit. In the Figures below a sketch of this simple device is shown. One tube, *the impact tube*, has its opening normal to the direction of flow and *the static tube* has its opening parallel to the direction of flow.



By applying Bernoulli's equation between points 1 and 2

$$\frac{p_1}{\rho g}+\frac{u_1^2}{2\alpha_1 g}+z_1=\frac{p_2}{\rho \alpha_2 g}+\frac{u_2^2}{2g}+z_2$$

$$u_1=\sqrt{\frac{2(-\Delta p)}{\rho}}=\sqrt{2\rho g h}=\sqrt{\frac{2R(\rho_m-\rho)}{\rho}} \text{where}, \Delta \mathrm{P} = \mathrm{R}(\rho_\mathrm{m}-\rho)\mathrm{g}$$

The fluid flows into the opening at point 2, pressure builds up, and then remains stationary at this point, called **"*Stagnation Point*"**. The difference in the *stagnation pressure* (impact pressure) at this point (2) and the static pressure measured by the static tube represent the pressure rise associated with the direction of the fluid.

Impact pressure head = Static pressure head + kinetic energy head

Since Bernoulli's equation is used for ideal fluids, therefore for real fluids the last equations of local velocity become:

$$u_1=Cp\sqrt{\frac{2(-\Delta p)}{\rho}}=Cp\sqrt{2\rho g h}=Cp\sqrt{\frac{2R(\rho_m-\rho)}{\rho}}$$

Where, Cp: dimensionless coefficient to take into account deviations from Bernoulli's equation and general varies between about 0.98 to 1.0.

Since the Pitot tube measures velocity at one point only in the flow, several methods can be used to obtain the average velocity in the pipe;

The first method, the velocity is measured at the exact center of the tube to obtain u_{max}. then by using the Figure, the average velocity can be obtained.

The second method, readings are taken at several known positions in the pipe cross section and then a graphical or numerical integration is performed to obtain the average velocity, from the following equation;

$$u=\frac{\iint_A u_x dA}{A}$$

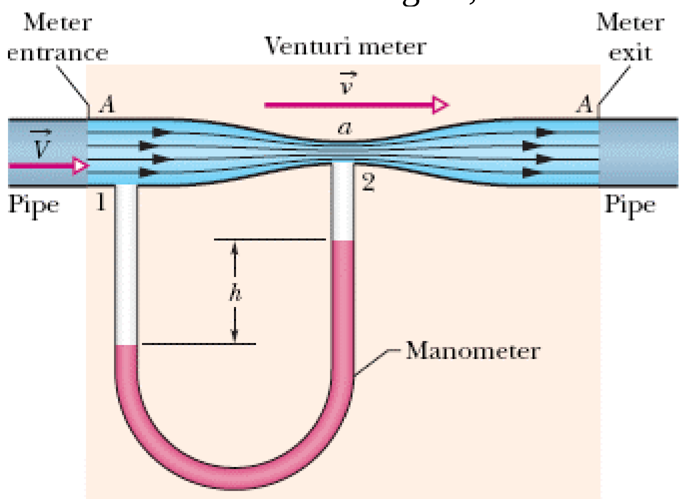
14.2.2 Measurement by Flow Through a Constriction

In measuring devices where the fluid is accelerated by causing it to flow through a constriction, the kinetic energy is thereby increased and the pressure energy therefore decreases. The flow rate is obtained by measuring the pressure difference between the inlet of the meter and a point of reduced pressure.

Venturi meters, *orifice meters*, and *flow nozzles* measure the volumetric flow rate Q or average (mean linear) velocity u. In contrast the Pitot tube measures a point (local) velocity ux.

14.2.2.1 Venturi Meter

Venturi meters consist of three sections as shown in Figure;



-From continuity equation $A_1u_1 = A_2u_2 \Rightarrow u_1 = (A_2/A_1)\, u_2$

- From Bernoulli's equation between points 1 and 2

$$\frac{p_1}{\rho g} + \frac{u_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{u_2^2}{2g} + z_2$$

$$z_1 = z_2$$

$$\frac{p_1 - p_2}{\rho g} = \frac{u_2^2 - u_1^2}{2g} = \frac{u_2^2}{2g}\left[1 - \left(\frac{A_2}{A_1}\right)^2\right] = \frac{u_2^2}{2g}\left[\frac{{A_1}^2 {A_2}^2}{{A_1}^2}\right]$$

$$u_2 = \sqrt{\frac{2(-\Delta p)}{\rho}\left[\frac{1}{1 - \left(\frac{A_2}{A_1}\right)^2}\right]} = \sqrt{\frac{2(-\Delta p)}{\rho}}\frac{A_1}{\sqrt{A_1 - A_2}}$$

$$u_2 = \sqrt{2g\Delta h\left[\frac{1}{1-\left(\frac{A_2}{A_1}\right)^2}\right]} = \sqrt{2g\Delta h}\frac{A_1}{\sqrt{A_1 - A_2}}$$

$$u_2 = \sqrt{\frac{2R(\rho_m - \rho)}{\rho}\left[\frac{1}{1-\left(\frac{A_2}{A_1}\right)^2}\right]} = \sqrt{\frac{2R(\rho_m - \rho)}{\rho}}\frac{A_1}{\sqrt{A_1 - A_2}}$$

All these equation of velocity ***at throat*** u2, which derived from Bernoulli's equation are for ideal fluids. Using a coefficient of discharge Cd to take account of the frictional losses in the meter and of the parameters of kinetic energy correction α1 and α2. Thus the volumetric flow rate will be obtained by: -

$$Q = u_2 A_2 = Cd\sqrt{\frac{2(-\Delta p)}{\rho}\left[\frac{{A_2}^2}{1-\left(\frac{A_2}{A_1}\right)^2}\right]} = Cd\sqrt{\frac{2(-\Delta p)}{\rho}}\frac{A_1 A_2}{\sqrt{{A_1}^2 - {A_2}^2}}$$

$$Or \qquad u_2 = Cd\sqrt{2g\Delta h\left[\frac{{A_2}^2}{1-\left(\frac{A_2}{A_1}\right)^2}\right]} = Cd\sqrt{2g\Delta h}\frac{A_1 A_2}{\sqrt{{A_1}^2 - {A_2}^2}}$$

$$Or \qquad u_2 = Cd\sqrt{\frac{2R(\rho_m - \rho)}{\rho}\left[\frac{{A_2}^2}{1-\left(\frac{A_2}{A_1}\right)^2}\right]} = Cd\sqrt{\frac{2R(\rho_m - \rho)}{\rho}}\frac{A_1 A_2}{\sqrt{{A_1}^2 - {A_2}^2}}$$

$$m^{\circ} = \rho Q = G = \rho u = \frac{m^{\circ}}{A}$$

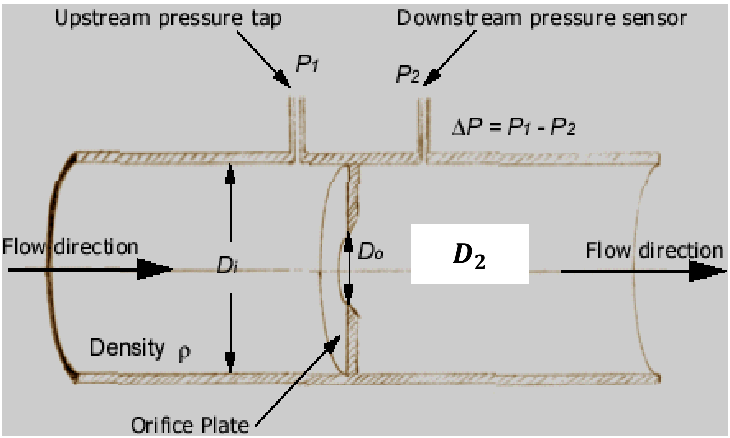
For many meters and for Re > 10^4 at point 1

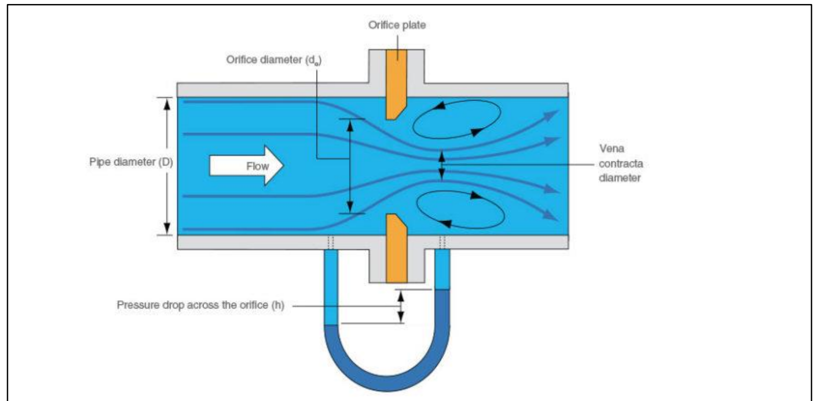
C_d = 0.98 for d_1 < 20 cm

C_d = 0.99 for d_1 > 20 cm

14.2.2.2 Orifice Meter

The primary element of an orifice meter is simply a flat plate containing a drilled located in a pipe perpendicular to the direction of fluid flow as shown in Figure;





An orifice plate with vena contracta

At point 2 in the pipe the fluid attains its maximum mean linear velocity u2 and its smallest cross-sectional flow area A_2. This point is known as "*the vena contracta*". It is occurs at about one-half to two pipe diameters downstream from the orifice plate.

Because of relatively the large friction losses from the eddies generated by the expanding jet below vena contracta, the pressure recovery in orifice meter is poor.

- From continuity equation $A_1u_1 = A_2u_2 \Rightarrow u_1 = (A_2/A_1)\,u_2$

- From Bernoulli's equation between points 1 and 2

$$\frac{p_1}{\rho g}+\frac{u_1^2}{2g}+z_1=\frac{p_2}{\rho g}+\frac{u_2^2}{2g}+z_2$$

$$z_1 = z_2$$

$$\frac{p_1-p_2}{\rho g}=\frac{u_2^2-u_1^2}{2g}=\frac{u_2^2}{2g}\left[1-\left(\frac{A_2}{A_1}\right)^2\right]=\frac{u_2^2}{2g}\left[\frac{{A_1}^2{A_2}^2}{{A_1}^2}\right]$$

But $C_c = A_2/A_o \Rightarrow A_2 = C_cA_o$

C_c: coefficient of contraction [0.6 – 1.0] common value is 0.67

A_2: cross-sectional area at vena contracta

A_o: cross-sectional area of orifice

$$\frac{p_1-p_2}{\rho}=\frac{u_2^2}{2}\left[1-\left(\frac{C_cA_\circ}{A_1}\right)^2\right]=\frac{u_2^2}{2}\left[\frac{{A_1}^2-(C_cA_\circ)^2}{{A_1}^2}\right]$$

Using a coefficient of discharge Cd to take into account the frictional losses in the meter and of parameters Cc, α1, and α2. Thus the velocity at orifice or the discharge through the meter is;

$$Q = Cd\sqrt{\frac{2(-\Delta p)}{\rho}\left[\frac{A_\circ{}^2}{1-\left(\frac{A_\circ}{A_1}\right)^2}\right]} = Cd\sqrt{\frac{2(-\Delta p)}{\rho}}\frac{A_1 A_\circ}{\sqrt{A_1{}^2 - A_\circ{}^2}}$$

$$Or \qquad u_2 = C_d\sqrt{2g\Delta h\left[\frac{A_\circ{}^2}{1-\left(\frac{A_\circ}{A_1}\right)^2}\right]} = C_d\sqrt{2g\Delta h}\frac{A_1 A_\circ}{\sqrt{A_1{}^2 - A_\circ{}^2}}$$

$$Or \qquad u_2 = C_d\sqrt{\frac{2R(\rho_m-\rho)}{\rho}\left[\frac{A_\circ{}^2}{1-\left(\frac{A_\circ}{A_1}\right)^2}\right]} = C_d\sqrt{\frac{2R(\rho_m-\rho)}{\rho}}\frac{A_1 A_\circ}{\sqrt{A_1{}^2 - A_\circ{}^2}}$$

$$m^\circ = \rho Q = G = \rho u = \frac{m^\circ}{A}$$

For many meters and for Re > 10^4 at point 1

$C_d = 0.98$ for $d_1 < 20$ cm

$C_d = 0.99$ for $d_1 > 20$ cm

$$Re = \frac{\rho u_\circ d_\circ}{\mu}$$

For $Re_o > 10^4$ $C_d = 0.61$
And for $Re_o > 10^4$ C_d From Figure below

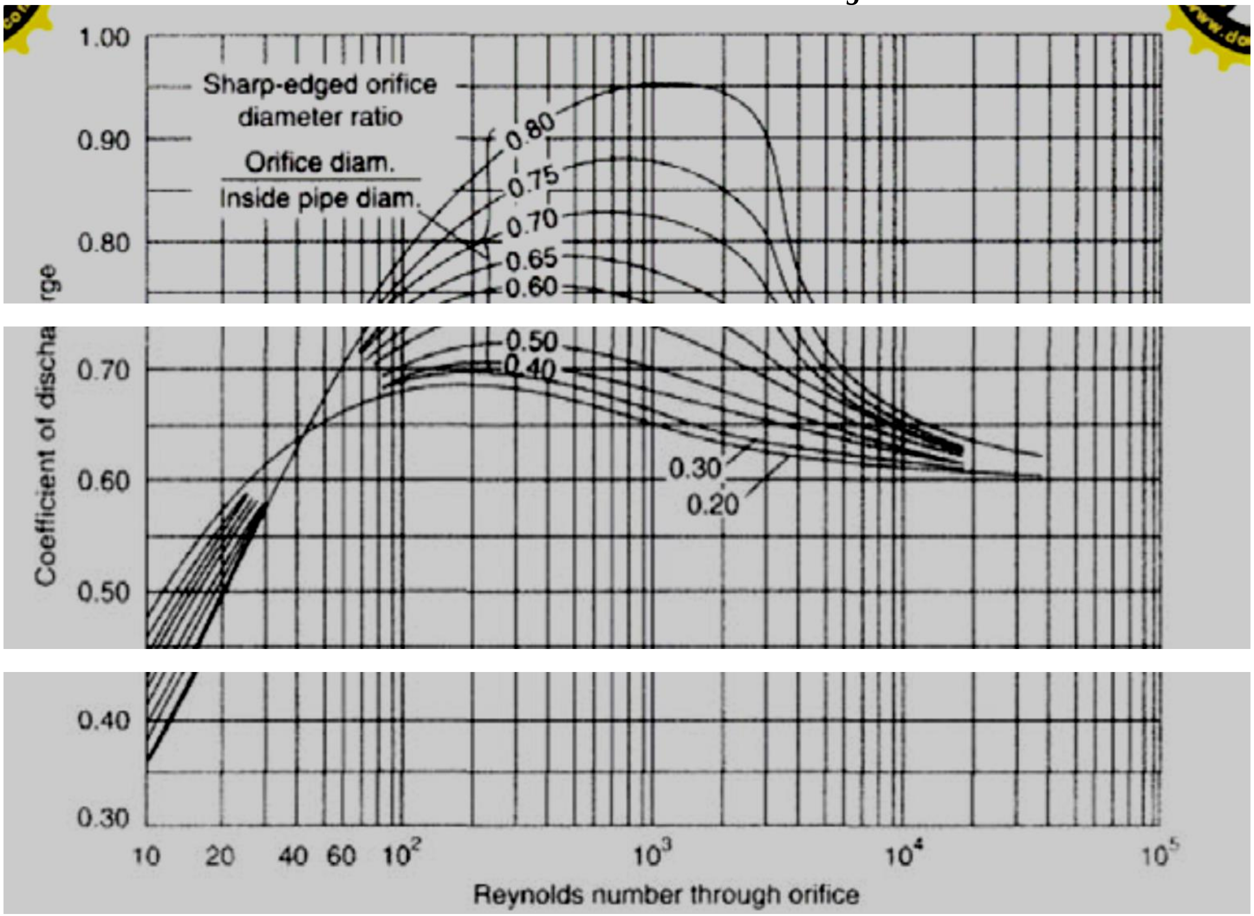


Figure of the discharge coefficient for orifice meter.

The holes in orifice plates may be ***concentric***, ***eccentric or segmental*** as shown in Figure. Orifice plates are prone to damage by erosion.

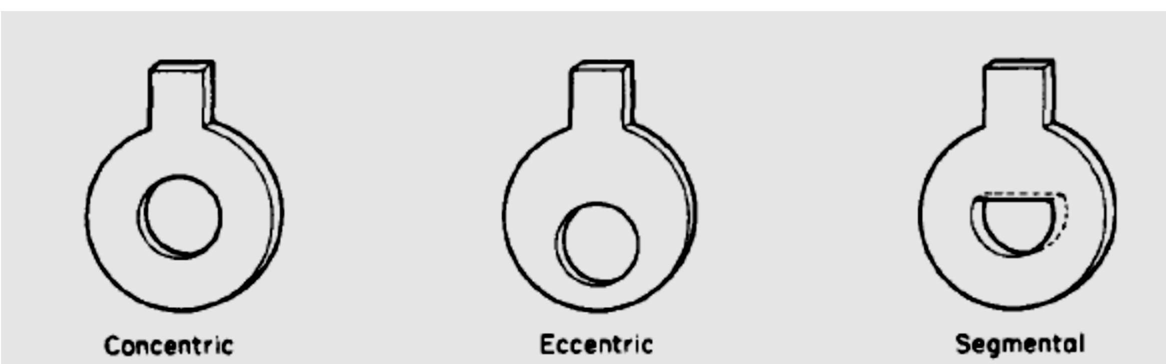
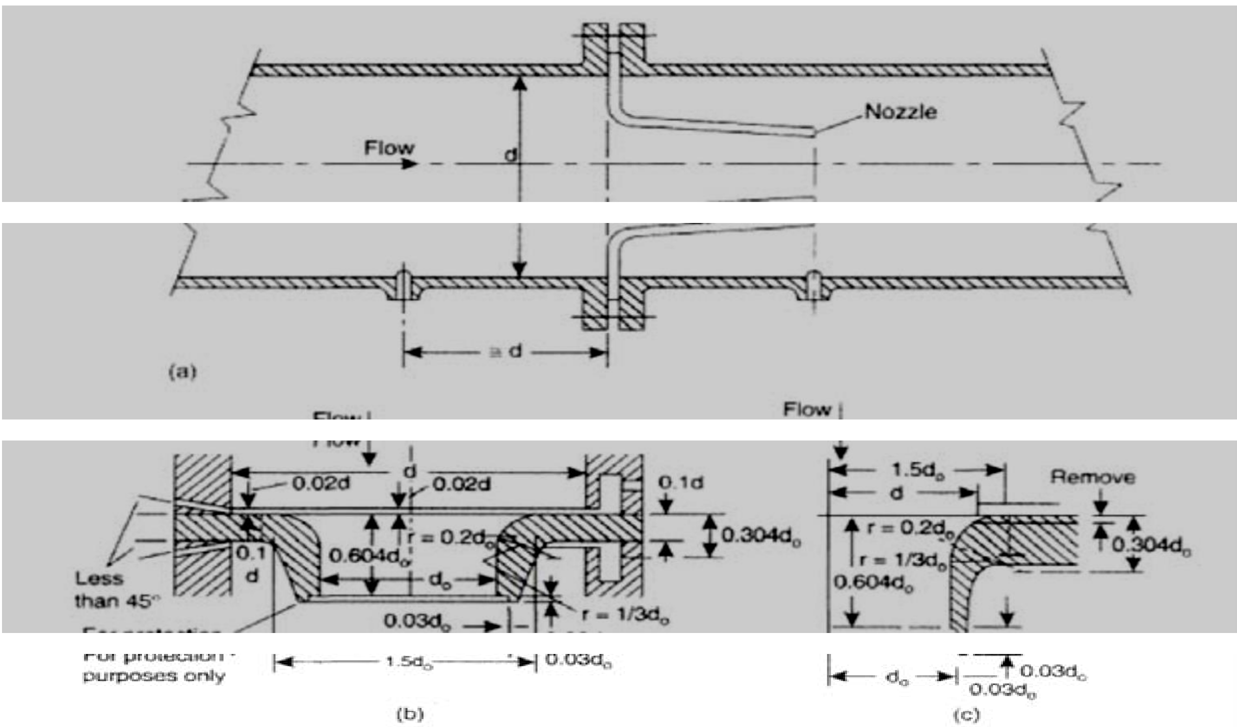


Figure of Concentric. eccentric and segmental orifice plates

14.2.2.3 The Nozzle

The nozzle is similar to the orifice meter other than that it has a *converging tube* in place of the orifice plate, as shown in below. The velocity of the fluid is gradually increased and the contours are so designed that almost frictionless flow takes place in the converging portion; the outlet corresponds to the *vena contracta* on the orifice meter. The nozzle has a constant high coefficient of discharge (ca. 0.99) over a wide range of conditions because the coefficient of contraction is unity, though because the simple nozzle is not fitted with a diverging cone, the head lost is very nearly the same as with an orifice. Although much more costly than the orifice meter, it is extensively used for metering steam. When the ratio of the pressure at the nozzle exit to the upstream pressure is less than the critical pressure ratio ωc, the flow rate is independent of the downstream pressure and can be calculated from the upstream pressure alone.



Figures of nozzle (a) General arrangement (b) Standard nozzle ((A_o/A_1) is less than 0.45. Left half shows construction for corner tappings. Right half shows construction for piezometer ring (c) Standard nozzle where (A_o/A_1) is greater than 0.45