Research Assistants
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FLOW METERS

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 moved through pipe, equipment, or the ambient atmosphere by pumps, fans, blowers, and compressors. Such devices increase the mechanical energy of the fluid. The energy increase may be used to increase the velocity, the pressure; or the elevation of the fluid. In the special case of liquid metals energy may be added by the action of rotating electromagnetic fields. The metering of fluids. is an important application of the energy balance. Basically, most flow meters are designed to cause a pressure drop that can be measured and related to the rate of flow. This pressure drop can be brought about by changes in kinetic energy, by skin friction, or by form friction. Some types of meters emphasize one or a combination of these mechanisms. Many different types of devices are used to measure the flow of fluids. The most simple are those that measure directly the volume of the fluids, such as ordinary gas and water meters and positive-displacement pumps. Current meters make use of an element such as a propeller or cups on a rotating arm which rotates at a speed determined by the velocity of the fluid passing through it. Very widely used for fluid metering are the pitoi tube, venturi meter, orifice meter, and open-channel weirs.

2. THEORY

2.1. Measurement of Flowing Fluids

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 Figure 1, 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.

The fluid flows into the opening at point 2, pressure builds up, and then remains stationary at this point, called the stagnation point. The difference in the stagnation pressure at this point 2 and the static pressure measured by the static tube represents the pressure rise associated with the deceleration of the fluid. 'The manometer measures this small pressure rise. If the fluid is incompressible, we can write the Bernoulli equation between point 1 and point 2, where the velocity U_1 is undisturbed before the fluid decelerates, and point 2, where the velocity U_2 is zero.

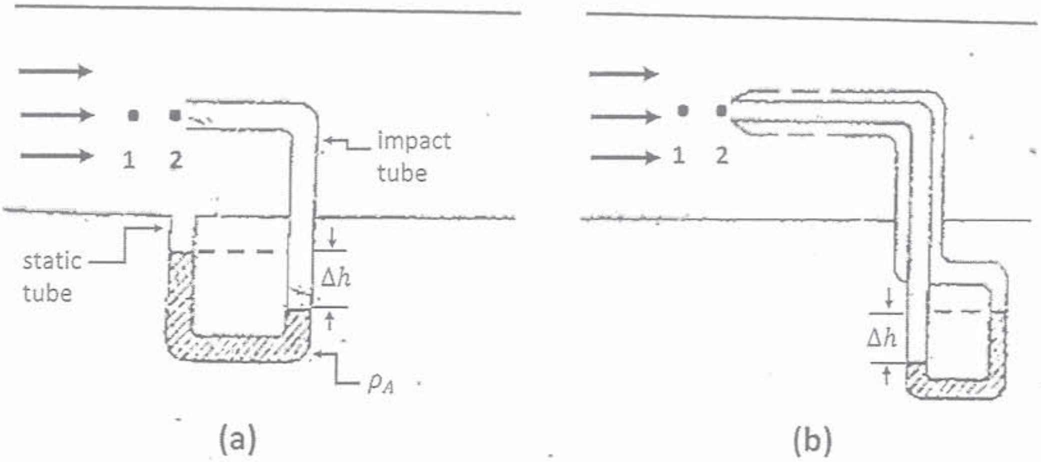


Figure 1. Diagram of pitot tube: (a) simple tube, (b) tube with static pressure holes

$$\frac{U_1^2}{2} - \frac{U_2^2}{2} + \frac{P_1 - P_2}{\rho} = 0 \quad (1)$$

Setting $U_2 \approx 0$ and solving for U_1

$$U = C_P \left[\frac{2(P_2 - P_1)}{\rho}\right]^{0.5} \quad (2)$$

where U is the velocity U_1 in the tube at point 1 in m/s, P_2 is the stagnation pressure, ρ is the density of the fluid at the static pressure P_1 and Cp is a dimensionless coefficient to take into account deviations from Eq. (1) and generally varies between about 0.98 and 1.0. For accurate use, the coefficient should be determined by calibration of the pitot tube. This equation applies to incompressible fluids but can be used to approximate the flow of gases at moderate velocities and pressure changes of about 10% or less of the total pressure. For gases the pressure change is often quite law and, hence, accurate measurement of velocities is difficult.

The value of the pressure drop, ΔP or (P_2-P_1) in Pa related to Δh, the reading on the manometer, by Eq. (3) as follows:

$$\Delta P = \Delta h(\rho_A - \rho)g \quad (3)$$

where ρ_A is the density of the fluid in the manometer in kg/m^3 and Δh is the manometer reading in m. In Figure 1(b), a more compact design is shown with concentric tubes. In the outer tube, the static pressure holes are parallel to the direction of flow.

Venturi meter

A venturi meter shown in Figure 2 and is usually inserted directly into a pipeline. A manometer or other device is connected to the pressure taps shown and measures the pressure difference P_1-P_2 between points 1 and 2. The average velocity at point 1 where the diameter is D_1 m is U_1 m/s, and at point 2 or the throat the velocity is U_2 and diameter D_2. Since the narrowing down from D_1 to D_2 and the expansion from D_2 back to D_1 is gradual, little fractional loss due to contraction and expansion is incurred.

To derive the equation for the venturi meter, friction is neglected and the pipe is assumed horizontal. Assuming turbulent flow and writing the mechanical-energy-balance Eq. (4) between points 1 and 2 for an incompressible fluid,

$$\frac{U_1^2}{2}+\frac{P_1}{\rho}=\frac{U_2^2}{2}+\frac{P_2}{\rho} \qquad (4)$$

The continuity equation for constant P is

$$U_1\frac{\pi D_1^2}{4}=U_1\frac{\pi D_2^2}{4} \qquad (5)$$

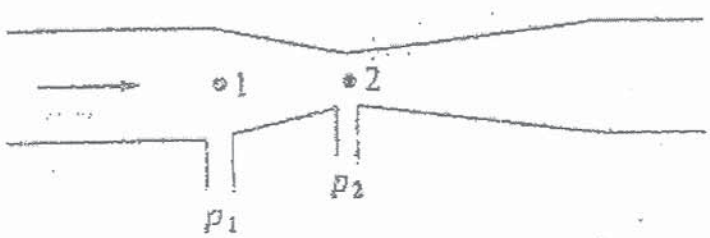


Figure 2. Venturi flow meter

Combining Eqns. (4) and (5) and eliminating U1,

$$U_2=\left[\frac{2(P_1-P_2)}{(1-(D_2-D_1)^4)\rho}\right]^{0,5} \qquad (6)$$

To account for the small friction loss an experimental coefficient Cv is introduced to give,

$$U_2=C_V\left[\frac{2(P_1-P_2)}{(1-(D_2-D_1)^4)\rho}\right]^{0,5} \qquad (7)$$

For many meters and a Reynolds number>10^4 at point 1, Cv is about 0.98 for pipe diameters below 0.2 m and 0.99 for larger sizes.

To calculate the volumetric flow rate, the velocity U_2 is multiplied by the area A_2

$$Q = C_V\left[\frac{2(P_1 - P_2)}{\left(1-(D_2/D_1)^4\right)\rho}\right]^{0.5} \frac{\pi D_2^2}{4} \qquad m^3/s \qquad (8)$$

The pressure difference P1-P2 occurs because the velocity is increased from lit to U2- However, farther down the tube the velocity returns to its original value of U1 for liquids. Because of some frictional losses, some of the difference P1-P2 is not fully recovered. In the venturi meter, the velocity is increased, and the pressure decreased, in the upstream cone. The pressure drop in the upstream cone is utilized so the velocity is decreased, and the original pressure largely recovered, in the downstream cone. To make the pressure recovery large, the angle of the downstream cone is small, so boundary-layer separation is prevented and the friction minimized. Since operation does not occur in a contracting cross section, the upstream cone can be made shorter than the downstream cone with but little friction, and space and material are thereby conserved.

Although venturi meters can be applied to the measurement of gases, they are most commonly used for liquids, especially water.

The venturi tube provides an accurate means for measuring flow in pipe lines. With suitable recording device the flow rate earl be integrated so as to give the total quantity of flow. Aside from the installation cost, the only disadvantage of the venturi meter is that it introduces a permanent frictional resistance in the pipeline.

For accuracy in use, the venturi meter should be preceded by a straight pipe whose length is at least 5 to 10 pipe diameters. The approach section becomes more important as the diameter ratio increases, and required length of straight pipe depends on the conditions preceding it, Thus the vortex formed from two short radius elbows in planes at right angles, for example, is not eliminated with 30 pipe diameters. Unless specific information is available for a given venturi tube, the value of C may be assumed to be about 0.97 or 0.98 for small ones, provided the flow is such as to give reasonably high Reynolds Numbers. A roughening of the surface of the converging section from ape or scale deposit will reduce the coefficient slightly. Venturi tubes in service for many years have shown a decrease in Cv of the order of 1 to 2 percent. Dimensional analysis of a venturi tube indicates that the coefficient Cv should be a function of Reynolds Number and of the geometric parameters D1 and D2. Values of venturi tube coefficients are shown in Figure 3. This diagram is for a diameter ratio of D2/D1= 0.25 to 0.75 with in the tolerances shown by the dotted lines.

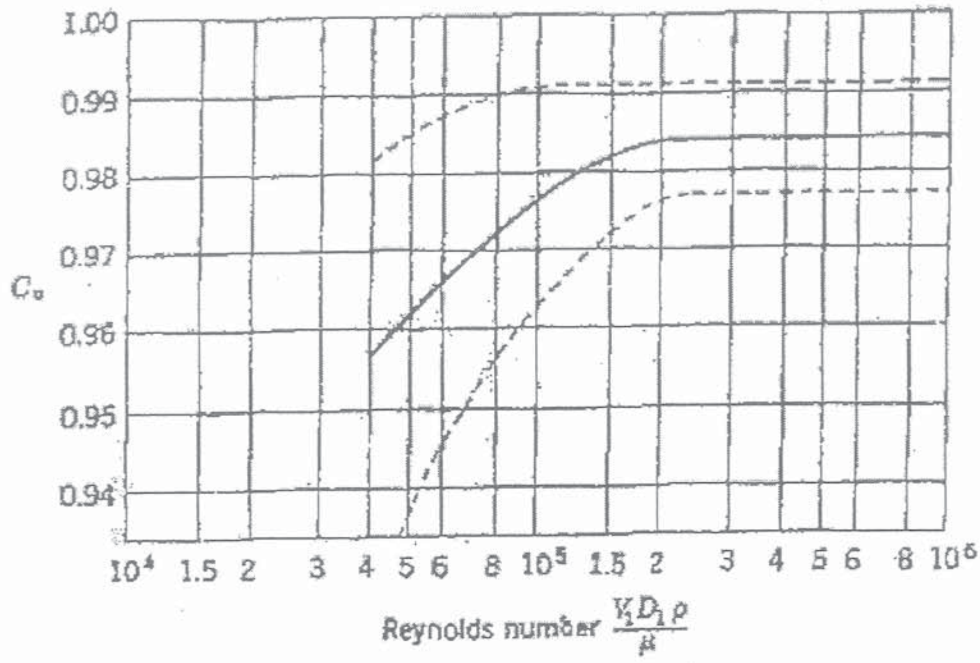


Figure 3. Coefficient C_v for venturimeters.

Orifice meter

For ordinary installations in a process plant the venturi meter has several disadvantages. It occupies considerable space and is expensive. Also, the throat diameter is fixed so that if the flow-rate range is changed considerably, inaccurate pressure differences may result. The orifice meter overcomes these objections but at the price of a much larger permanent head or power loss.

A typical sharp-edged orifice is shown in Figure 4. A machined and driller plate having a hole of diameter D_o is mounted between two flanges in a pipe of diameter D_1. Pressure taps at point 1 upstream and 2 down stream measure P_1-P_2. The exact positions of the two taps are somewhat arbitrary, and 0.3 to 0.8 pipe diameter downstream. The fluid stream, once past the orifice plate, forms a vena contracta of free-flowing jet.

The equation for the orifice meter is similar to Eq. (8):

$$Q = U_o \frac{\pi D_2^2}{4} \qquad (9)$$

$$Q = C_o \left[\frac{2(P_1 - P_2}{(1 - \left(\frac{D_2}{D_1}\right)^4)\rho} \right]^{0.5} \frac{\pi D_2^2}{4} \qquad (10)$$

where U_o is the velocity in te orifice in m/s, Q is the volumetric flow rate in the orifice in m^3/s, D_o is the orifice diameter in m, and C_o is always determined experimentally.

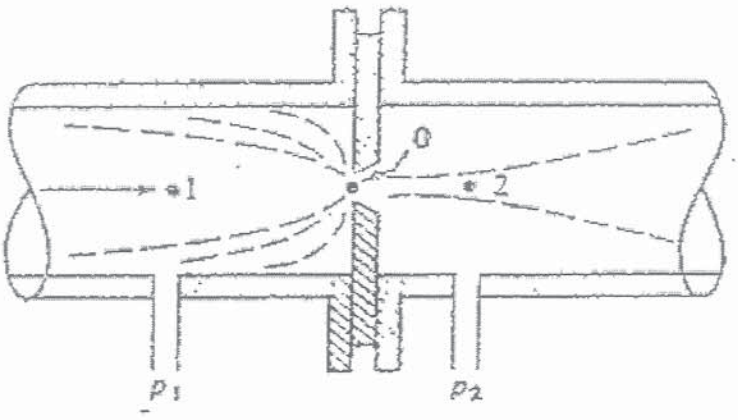


Figure 4. Orifice flow meter

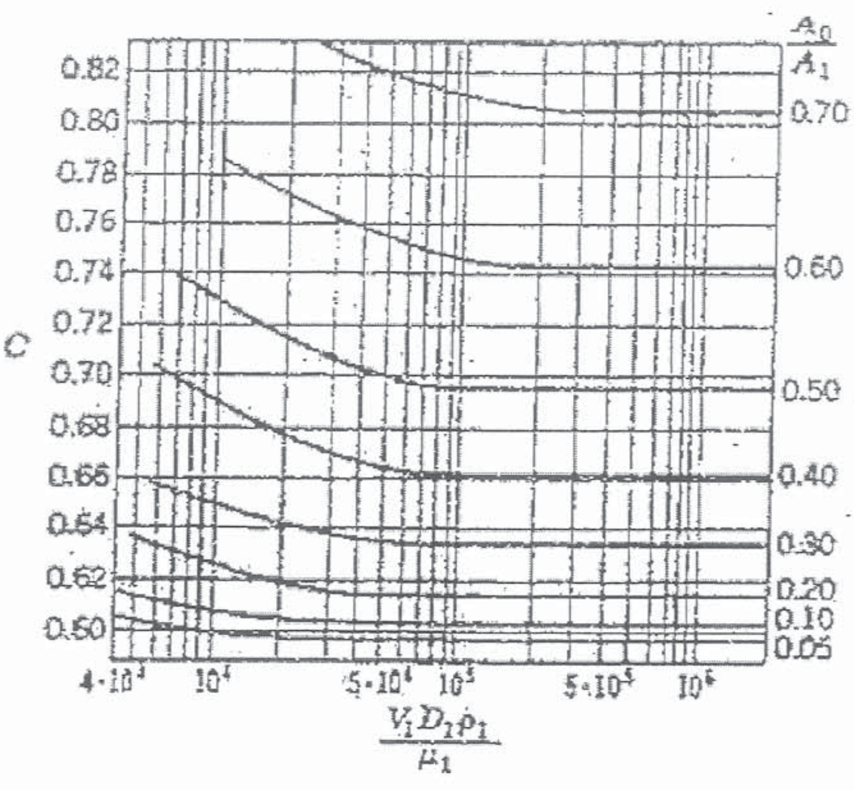


Figure 5. Coefficient for orifice meters

Typical values of $C(=C_o)$ for a standard orifice meter are given in Figure 5. The variation of C with Reynolds Number is quite different than the trend of the flow coefficients for venturi tubes. At high Reynols Numbers C is essentially constant, but as the Reynols Number is lowered, an increase in the value of C for the orifice is noted with maximum value of occuring at Reynolds Numbers between 4000 to 10000, depending on the Ao/A_1 ratio of the orifice area/pipe area.

Rotameter

The rotameter (Figure 6) consists of a vertical glass tube that is slightly tapered, in which the metering float is suspended by the upward motion of the fluid arround it. Directional notches cut in the float keep it rotating and thus free of wall friction. The rate of flow determines the equilibrium height of the float, and the tube is graduated to read flow directly. The rotameter is also used for gas flow, but the weight of the float and the graduation must be changed according to flow rate.

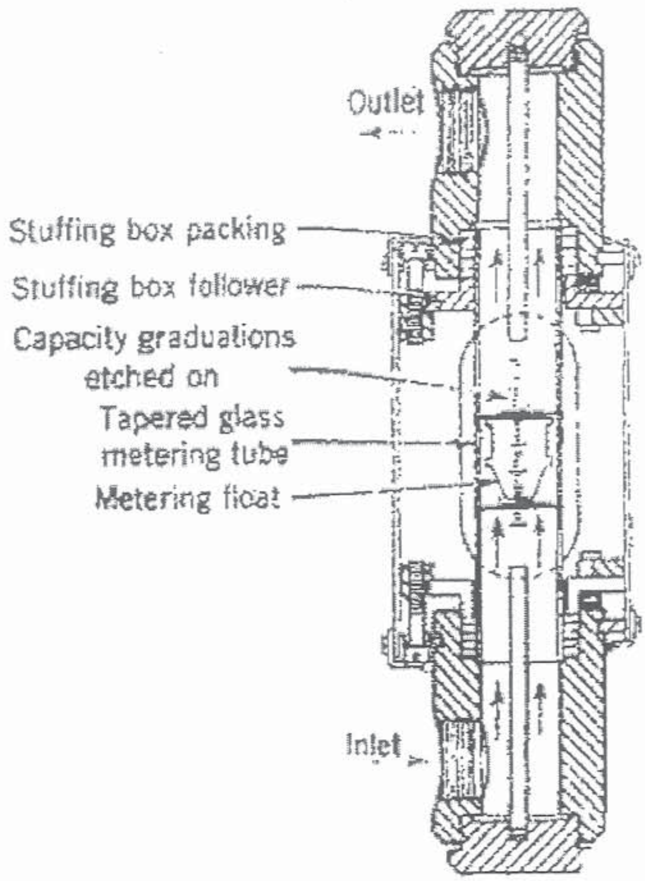


Figure 6. Rotameter

For a given flow rate, the equilibrium position of the float in a rotameter is established by a balance of three forces. (1) the weight of the float, (2) the buoyant force of the fluid on the float, and (3) the drag force on the float. Force 1 acts downward, 2 and 3 upward.

For equilibrium;

$$-\Delta P A_f = F_D = V_f \rho_f g - V_f \rho g \qquad (11)$$

where; ΔP: Pressure difference acting on float, F_D: drag force, g: Acceleration of gravity, V_f: Volume of float, ρ_f: Density of float, ρ: Density of fluid.

Applying the Bernoulli's Equation,

$$\dot{m} = \frac{C_f a}{(1-\left(\frac{a}{A}\right)^2)^{0.5}} \cdot \left[\frac{2gV_f(\rho_f-\rho)}{A_f}\right]^{0.5} \qquad (12)$$

where; A: cross-sectional area of rotameter; A_f: cross-sectional area of float; a: flowing area of fluid (A-A_f).

Rotameters tend to have a nearly linear relationship between flow and position of the float compared with a calibration curve an orifice meter, for which the flow rate is proportional to the square root of the reading.

2.2. Flow Measurement of Compressible Fluids

Strictly speaking, most of the equations that have been presented in the preceding part of this section only to incompressible fluids, but practically, that may be used for all liquids and even for gases and vapors where the pressure differential is small relative to the total pressure. As this is the condition usually encountered in the metering of all fluids, even compressible ones, the preceding treatment has extensive application. However, there are conditions in metering fluids where compressibility must be considered.

As in the case of incompressible fluids, equations may be derived for ideal frictionless flow and then a coefficient introduced to obtain a correct result. The ideal condition that will be imposed on the compressible fluid is that the flow be isentropic, i.e., frictionless adiabatic process (no transfer of heat). The latter is practically true for metering devices, as the time for the fluid to pass through is so short that very little heat transfer can take place. An expression applicable to pitot tubes for subsonic flow of compressible fluids can be derived by introducing the conditions at the upstream tip of the tube (that is, V_2=0 and V_1=0) in Eq. (13).

$$\frac{V_2{}^2-V_1{}^2}{2}=\frac{P_1}{\rho_1}\frac{k}{k-1}\left[1-\left(\frac{P_2}{P_1}\right)^{k-1/k}\right]-\frac{P_2}{\rho_2}\frac{k}{k-1}\left[1-\left(\frac{P_1}{P_2}\right)^{k-1/k}\right] \quad (13)$$

Substituting the first expression for R and q in case of $V_2=0$ from Eq. series (14)

$$C_p{}' = {kR}/{k-1} \text{ and } C_v{}' = {R}/{k-1} \text{ and } \rho = {P}/{RT} \quad (14)$$

where, k is the ratio of specific heats at constant prssure and volume. C_p/C_v

Doing so gives for pitot tubes,

$$\frac{V_1^2}{2}=C_pT_1\left[\left(\frac{P_2}{P_1}\right)^{k-1/k}-1\right]=C_pT_2\left[\left(1-\frac{P_1}{P_2}\right)^{k-1/k}\right] \quad (15)$$

The static pressure P1 may be obtained from the sid openings of the pitot tube from a regular piezometer, and the stagnation pressure $P_s(=P_2)$ is indicated by pitot tube itself. A coeficient must be applied if the side openings do not measure the true static pressure. Eq (15) doesn't apply to supersonic conditions because a shock wave would from upstream of the stagnation point. In such a case a special analysis considering the effect of the shock wave is required.

To develop an expression applicable to compressible flow through venturi tubes we take Eq. (13) and combine it with continuity $\rho_1A_1V_1\text{-}\rho_2A_2V_2$ to get

$$\dot{m_{ideal}}=A_2\left[2\left[\frac{k}{k-1}\right]P_1\rho_1\left[\frac{P_2}{P_1}\right]^{-1/k}\right]\left[1-\frac{\left({P_2}/{P_1}\right)^{(k-1)/k}}{(A_2/A_1)^2\left({P_2}/{P_1}\right)^{2/k}}\right]^{0.5} \quad (16)$$

This equation can be transformed into an equation fort he actual weight rate of flow through venturi tubes by introducing the discharge C_v (Figure 3) and an expansion factor Y. The resulting equation is,

$$\dot{m}=C_vYA_2\left\{\left\{2\rho_1-\frac{(P_1-P_2)}{\left(1-\left({D_2}/{D_1}\right)\right)^4}\right\}\right\}^{0.5} \quad (17)$$

Y is a dimensionless expansion factor which is the function of P_2/P_1 ($=P_b/P_a$) and β that is equal to D_2/D_1 ratio.

In Eq. (17), C_v has the same value as for an incompressible fluid at the same Reynolds Number and ρ_1 may be replaced by P_1/RT_1 if desired. Values of Y for k=1.4 are plotted in Figure 7.p. The Eq. (17) can also be used for flow nozzles and orifice meters, through for flow nozzles C_v should be replaced.

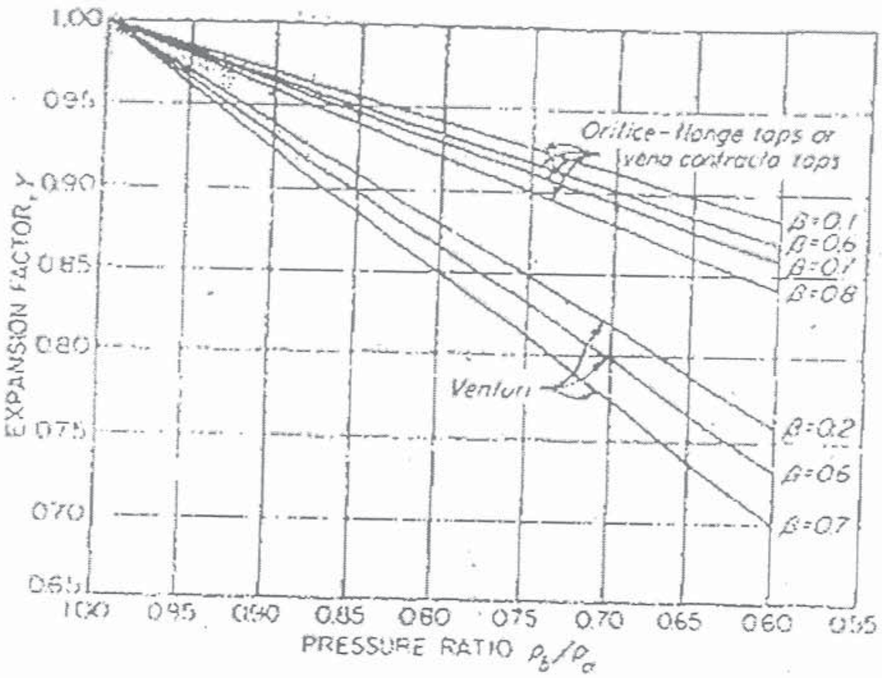
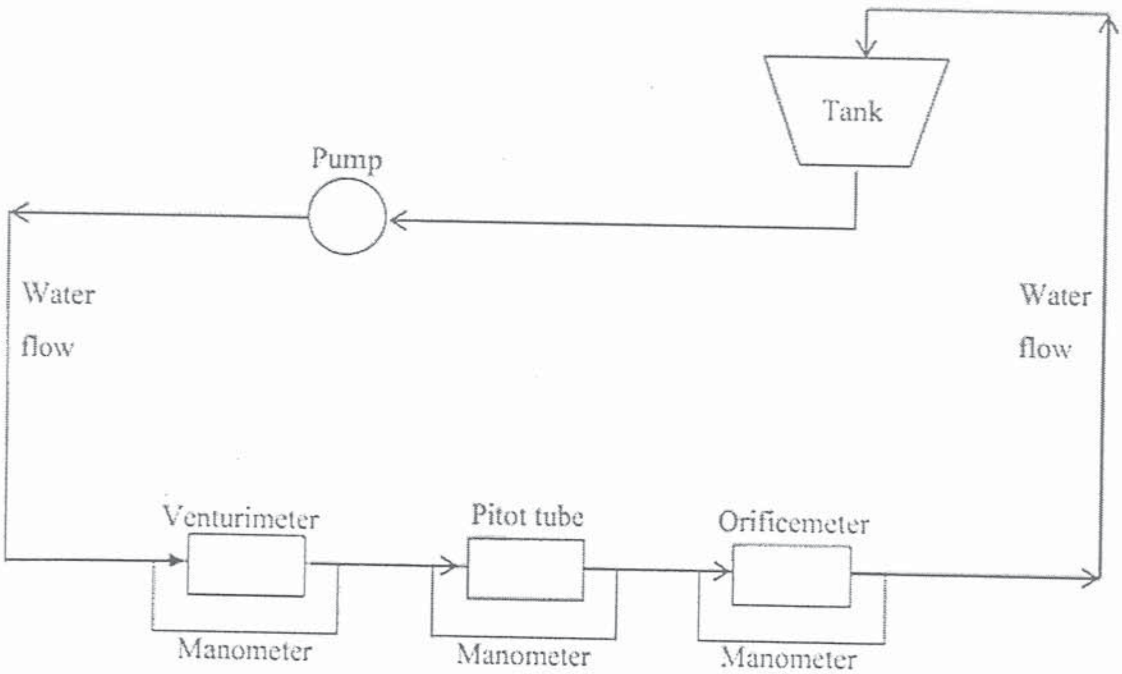


Figure 7. Expansion Factors

3. EXPERIMENTAL SECTION

3.1 Experimental Set Up



(a)

SYMBOLS

A : Area, ft^2 or m^2, a: of flowing fluid, A_f: of float, A_o: of orifice meter, A_1, A_2: at stations 1 and 2

C_o : Orifice coefficient, velocity approach not included, dimensionless

C_p : Pitot tube coefficient, dimensionless

C_R : Rotameter calibration coefficient, dimensionless

C_v : Venturi coefficient, velocity approach not included, dimensionless

C_P : Molar specific heat at constant pressure, Btu/lbmol °F or J/gmol K

C_V : Molar specific heat at constant volume, Btu/lbmol °F or J/gmol K

D : Diameter, ft or m; D_o: Orifice diameter; D_i: Inlet diameter; D_2: Venturi throat diameter

F_D : Drug force, lb_f or N

g : gravitational acceleration, ft/s^2 or m/s^2

h : Reading of manometer ft or m; Δh: difference in reading of manometer

k : Ratio of specific heats, dimensionless, C_P/C_V

m : Mass flow rate, lb/s or kg/s

R : gas-law constant, 1.545 ft-lb/lbmol.°R or 8.314 J/kg mol-K

P : Pressure, lb_f/ft^2 or atm; ΔP: difference acting on float; P_s: Impact pressure; P_o: static pressure; P_1, P_2 at stations 1 and 2

Q : Volumetric flow rate, ft^3/s or m^3/s

V_f : Volume of rotameter float, ft^3 or m^3

U : Local fluid velocity, ft/s or m/s; U_1, U_2 at stations 1 and 2

V : Resultant velocity, ft/s or m/s; V_1, V_2 at stations 1 and 2

Y : Expansion factor

Z : Height above datum plane, ft or m; Z_1, Z_2 at stations 1 and 2

Greek letters

β : Ratio of flow meter area/pipe area, dimensionless

ρ : Density, lb/ft^3 or kg/m^3; ρ_f: of rotameter float, ρ_1, ρ_2: molar density at stations 1 and 2, $lbmol/ft^3$ or $kgmol/m^3$

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Surname / Name: Date:

Group No:

DATA SHEET

Experiment : Flowmeters

Orificemeter calibration for water (V= .....) L		Venturimeter calibration for water (V= .....) L	
h (mm water)	t (s)	h (mm water)	t (s)
Pitotmeter calibration for water (V= .....) L		**Rotameter calibration for water (V= .....) L**	
h (mm water)	t (s)	Q ( )	t (s)

Air velocity :

Angle of inclined manometer : 30°

Density of the inclined manometer fluid :

$P_1 - P_2 = \ldots..$

$P_1 - P_{atm} = \ldots..$