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Experiment No. 5: flow measurement apparatus

Introduction:

There are many different meters used to measure fluid flow: the rotameter, the orifice meter, and the Venturi meter are only a few. Each meter works by its ability to alter a certain physical property of the flowing fluid and then allows this alteration to be measured. The measured alteration is then related to the flow.

The apparatus in our experiment is designed such a way that to measure flow rate using different type of flow measuring devices such as venturi meter, orifice and rotameter.

-Water enters venturi meter along the pipe until a certain distance.

-Then, it passes through the orifice plate meter.

-The flow continues till meets right-angled bend and flows into rotameter.

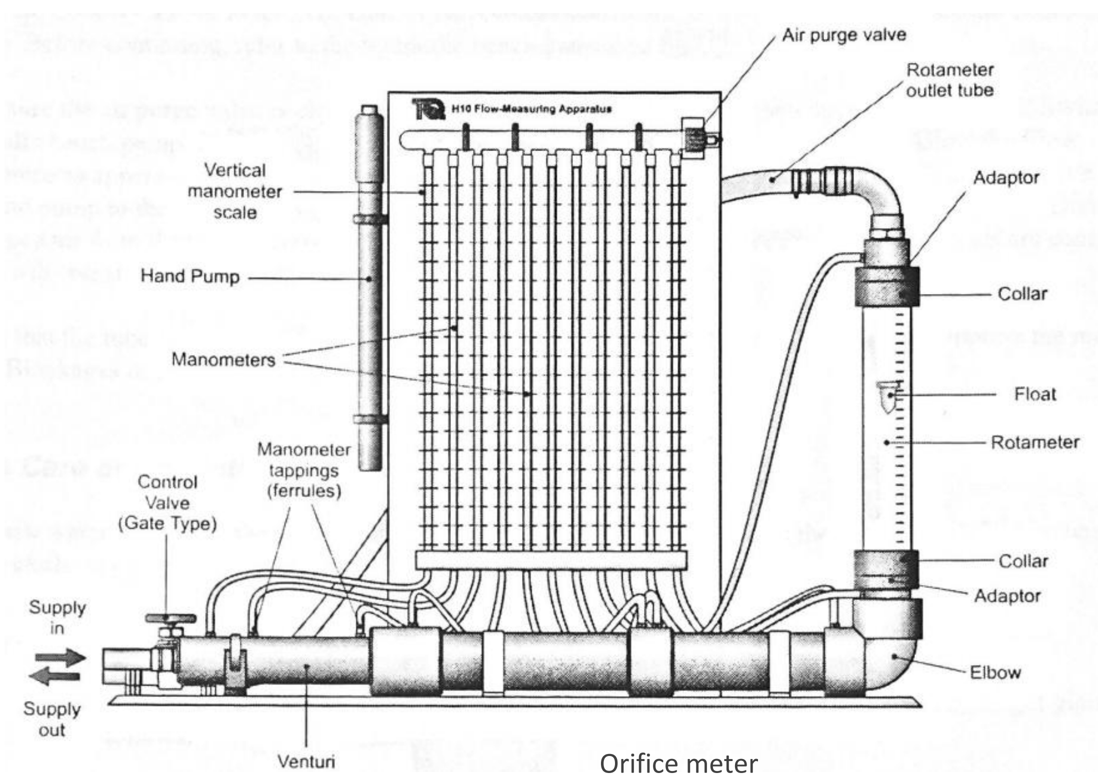


Fig. 1: flow measurement apparatus

Objectives:

This experiment allows the student to:

1. demonstrate typical **flow rate measurement** devices for incompressible fluids in pipes: (1) Venturi meter, (2) Orifice plate, and (3) Rotameter.
2. compared Each flow measurement device to the standard method of using the catch-tank and stopwatch to measure the flow rate.
3. determine the **energy loss** incurred by each of these devices.
4. use the Bernoulli equation and steady-state energy equation.

Parts needed:

1. H10 flow measurement apparatus, (fig.*2a*).
2. H1D volumetric bench, (fig.*2b*)
3. Hand pump.
4. Stopwatch.
5. Colored water.

Fig.2a: H10 flow measurement apparatus

Fig. 2b:H1D volumetric bench

Theory:

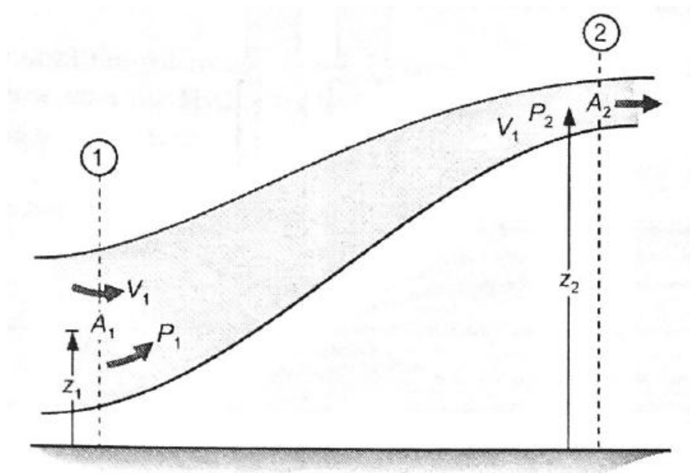


Fig. 3: the steady flow energy equn

For steady, adiabatic flow of an incompressible fluid along a stream tube, as shown in figure3, Bernoulli's equation can be written in the form:

$$\frac{p_1}{\rho g} + \frac{\overline{V}_1^{\,2}}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{\overline{V}_2^{\,2}}{2g} + z_2 + \Delta H_{12} \qquad (1)$$

Where:

$\frac{p}{\rho g}$ = Hydrostatic head;

$\frac{\overline{V}^2}{2g}$ = Kinetic Head ($\overline{V}$ is the mean velocity, i.e. the ratio of volumetric discharge to cross sectional area of tube)

z = Potential Head

$\frac{p}{\rho g} + \frac{\overline{V}^2}{2g} + z$ = Total Head

The head loss ΔH_{12} may be assumed to arise as a consequence of the vortices in the stream. Because the flow is viscous a wall shear stress exists and a pressure force must be applied to overcome it. The consequent increase in flow work appears as an increase in internal energy, and because the flow is viscous, the velocity profile at any section is non-uniform.

The kinetic energy per unit mass at any section is then greater than $V^2/2g$ and Bernoulli's Equation incorrectly assesses this term. The fluid mechanics entailed in all but the very simplest internal flow problems are too complex to permit the head loss ΔH to be determined by any other means than experimental. Since a contraction of stream boundaries can be shown (with incompressible fluids) to increase flow uniformity and a divergence correspondingly decreases it, ΔH is typically negligibly small between the ends of a contracting duct but is normally significant when the duct walls diverge.

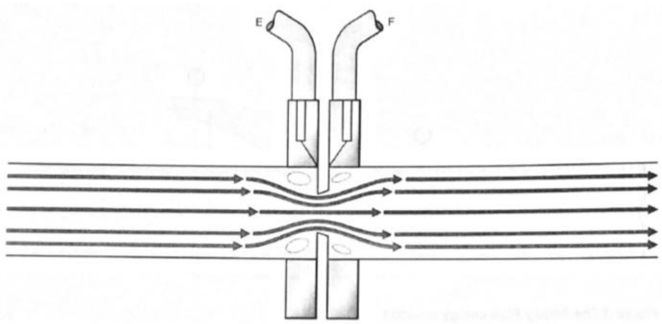
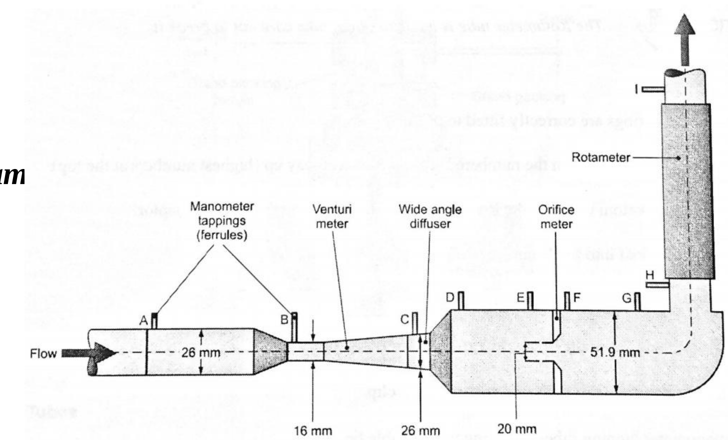


Fig. 4: construction of the orifice meter

Calculations of Discharge

The Venturi meter, the orifice plate meter and the rotameter are all dependent upon Bernoulli's Equation for their principle of operation. The following have been prepared from a typical set of results to show the form of the calculations.

Fig. 5:explanatorydiagram of the flow measurement apparatus



Venturi Meter

Since ΔH_{12} is negligibly small between the ends of a contracting duct it, along with the Z terms, can be omitted from Equation (1) between stations (A) and (B).

From continuity:

$$\rho V_A A_A = \rho V_B A_B \tag{2}$$

The discharge:

$$Q = A_B V_B = A_B \left[\left(\frac{2g}{1 - \left(\frac{A_B}{A_A} \right)^2} \right) \left(\frac{p_A}{\rho g} - \frac{p_B}{\rho g} \right) \right]^{\frac{1}{2}} \tag{3}$$

With the apparatus provided, the bores of the meter at (A) and (B) are 26 mm and 16 mm respectively, so:

$$\frac{A_B}{A_A} = 0.38 \text{ and } A_B = 2.01 \times 10^{-4} \text{m}^2$$

Since $g = 9.81$ m.s^{-2} and $\frac{p_A}{\rho g}, \frac{p_B}{\rho g}$ are the respective heights of the manometric tubes A and B in metres, we have from equation (3):

$$Q = 9.62 \times 10^{-4} (h_A - h_B)^{\frac{1}{2}} \text{ m}^3/\text{s} \qquad (4)$$

Taking the density of water as 1000 kg/m^3, the mass flow will be:

$$m = 0.962 \times (h_A - h_B)^{\frac{1}{2}} \text{ kg/s}$$

For example, if $h_A = 375$ mm and $h_B = 110$ mm, then:

$$(h_A - h_B)^{\frac{1}{2}} = 0.51$$

and

$$m = 0.962 \times 0.51 = 0.49 \text{ kg/s}$$

(The corresponding Hydraulic Flow Bench assessment was 0.48 kg/s).

Orifice Meter

Between tappings (E) and (F) ΔH_{12} in Equation (1) is by no means negligible. Rewriting the equation with the appropriate symbols:

$$\frac{\overline{V}_F^{\,2}}{2g} - \frac{\overline{V}_E^{\,2}}{2g} = \left(\frac{p_E}{\rho g} - \frac{p_F}{\rho g}\right) - \Delta H_{12} \qquad (5)$$

such that the effect of the head loss is to make the difference in manometric height (h_E - h_F) less than it would otherwise be. An alternative expression is:

$$\frac{\overline{V}_F^{\,2}}{2g} - \frac{\overline{V}_E^{\,2}}{2g} = C^2\left(\frac{p_E}{\rho g} - \frac{p_F}{\rho g}\right) \qquad (6)$$

where the coefficient of discharge C is given by previous experience in BS1042 (1981) for the particular geometry of the orifice meter. For the apparatus provided, C is given as 0.601.

Reducing the expression in exactly the same way as for the Venturi meter,

$$Q = A_F \bar{V}_F = C A_F \left[\left(\frac{2g}{1 - \left(\frac{A_F}{A_E} \right)^2} \right) \left(\frac{p_E}{\rho g} - \frac{p_F}{\rho g} \right) \right]^{\frac{1}{2}} \qquad (7)$$

With the apparatus provided, the bore at (E) is 51.9 mm and at (F), the water diameter is 20 mm, then:

$$Q = 9.06 \times 10^{-4} (h_E - h_F)^{\frac{1}{2}} \ \text{m}^3/\text{s}$$

Thus

$$m = \cancel{0.846}\ 0.906 \times (h_E - h_F)^{\frac{1}{2}} \ \text{kg/s}$$

For example, if

$h_E = 372$ mm and

$h_F = 40$ mm,

then,

$$(h_E - h_F)^{\frac{1}{2}} = 0.58$$

and

$$m = 0.906 \times 0.58 = 0.53 \ \text{kg/s}$$

(The corresponding Hydraulic Flow Bench assessment was 0.48 kg/s.)

Rotameter

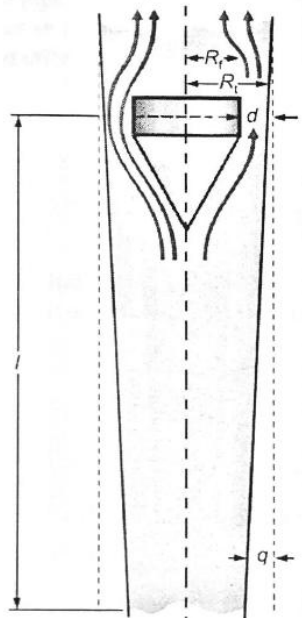


Fig.6: principle of the rotameter

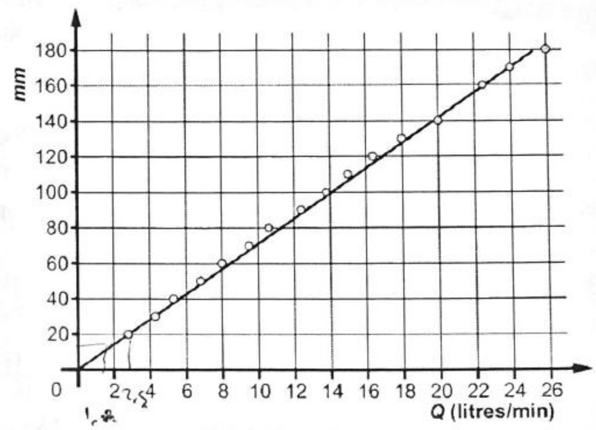


fig. 7: typical rotameter calibration curve

Observation of the recordings for the pressure drop across the rotameter (H) - (I) shows that this difference is large and virtually independent of discharge. There is a term, which arises because of wall shear stresses, and is therefore velocity dependent, but since the rotameter is of large bore this term is small. Most of the observed pressure difference is required to maintain the float in equilibrium and since the float is of constant weight, this pressure difference is independent of discharge.

The cause of this pressure difference is the head loss associated with the high velocity of water around the float periphery. Since this head loss is constant then the peripheral velocity is constant. To maintain a constant velocity with varying discharge rate, the cross-sectional area through which this high velocity occurs must vary. This variation of cross-sectional area will arise as the float moves up and down the tapered rotameter tube.

From figure 6 , if the float radius is R_f and the local bore of the rotameter tube is $2R_1$ then:

$$\pi(R_t^2 - R_f^2) = 2R_f^2\delta = \text{Cross Sectional Area} = \frac{\text{Discharge}}{\text{Constant Peripheral Velocity}}$$

Now $\delta = l\theta$, where l is the distance from datum to the cross-section at which the local bore is R_t and θ is the semi-angle of tube taper.

Hence l is proportional to discharge. An approximately linear calibration characteristic would be anticipated for the Rotameter (see figure 7).

Calculations of Head Loss

By reference to Equation (1), the head loss associated with each meter can be evaluated.

Venturi Meter

Applying the equation between pressure tappings (A) and (C).

$$\frac{p_A}{\rho g} - \frac{p_C}{\rho g} = \Delta H_{AC} \text{ so } h_A - h_C = \Delta H_{AC}$$

This can be made dimensionless by dividing it by the inlet kinetic head $\frac{\bar{V}_A^{\,2}}{2g}$.

Now,

$$\bar{V}_B^{\,2} = \frac{2g}{1 - \left(\frac{A_B}{A_A}\right)^2}\left(\frac{p_A}{\rho g} - \frac{p_C}{\rho g}\right)$$

and

$$\bar{V}_A^{\,2} = \bar{V}_B^{\,2}\left(\frac{A_B}{A_A}\right)^2$$

thus

$$\bar{V}_A^{\,2} = \left(\frac{A_B}{A_A}\right)^2\left[\left(\frac{1}{1 - \left(\frac{A_B}{A_A}\right)^2}\right)\left(\frac{p_A}{\rho g} - \frac{p_B}{\rho g}\right)\right]$$

With the apparatus provided $(A_B/A_A) = 0.38$, therefore the inlet kinetic head is:

$$\frac{\bar{V}_A^{\,2}}{2g} = 0.144 \times 1.16\left(\frac{p_A}{\rho g} - \frac{p_B}{\rho g}\right) = 0.167(h_A - h_B)$$

For example, if:

$h_A = 375$ mm,

$h_B = 110$ mm,

$h_C = 350$ mm,

then $\Delta H_{AC} = h_A - h_C = 25$ mm

$$\frac{\bar{V}_A^{\,2}}{2g} = 0.167(h_A - h_B) = 0.167 \times 265$$

Orifice Meter

Applying Equation (1) between (E) and (F) by substituting kinetic and hydrostatic heads would give an elevated value to the head loss for the meter. This is because at an obstruction such as an orifice plate, there is a small increase in pressure on the pipe wall due to part of the impact pressure on the plate being conveyed to the pipe wall. BS1042 (Section 1.1 1981) gives an approximate expression for finding the head loss and generally this can be taken as 0.83 times the measured head difference.

Therefore:

$$\Delta H_{EF} = 0.83(h_E - h_F) \text{ mm}$$

$$= 0.83\ (372 - 40) \text{ mm} = 275 \text{ mm}$$

The orifice plate diameter (51.9 mm) is approximately twice the Venturi inlet diameter (26 mm), therefore the orifice inlet kinetic head is approximately 1/16 that of the Venturi, thus:

$$\frac{44.26}{16} = 2.76$$

Therefore,

$$\text{Head Loss} = \frac{275}{2.76} = 99.6 \text{ inlet kinetic heads}$$

Rotameter

For this meter, application of Equation (1) gives:

$$\left(\frac{p_H}{\rho g} + z_H\right) - \left(\frac{p_I}{\rho g} + z_I\right) = \Delta H_{HI}$$

Then, as illustrated in figure 8:

$$h_H - h_I = \Delta H_{HI}$$

Inspection of the table of experimental results shows that this head loss is virtually independent of discharge and has a constant value of approximately 100 mm of water. As has already been shown, this is a characteristic property of the rotameter. For comparative purposes it could be expressed in terms of the inlet kinetic head. However, when the velocity is very low the head loss remains the same and so becomes many, many times the kinetic head.

It is instructive to compare the head losses associated with the three meters with those associated with the rapidly diverging section, or wide-angled diffuser, and with the right-angled bend or elbow. The same procedure is adopted to evaluate these losses.

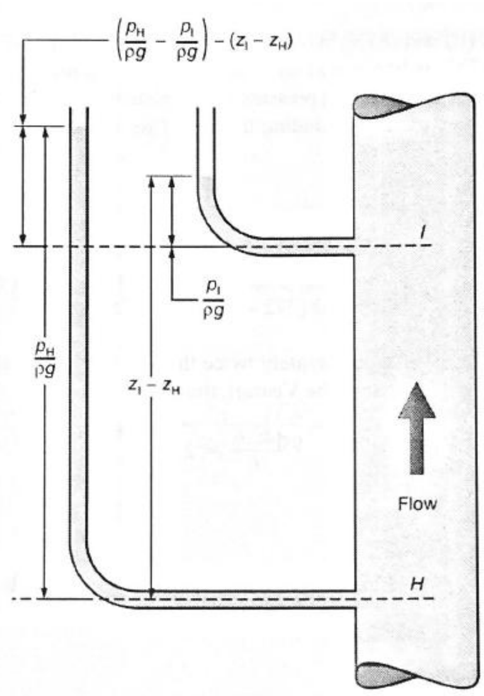


Fig. 8: rotameter head loss

Wide-Angled Diffuser

The inlet to the diffuser may be considered to be at (C) and the outlet at (D). Applying Equation (1):

$$\frac{p_C}{\rho g} + \frac{\overline{V}_C^{\,2}}{2g} = \frac{p_D}{\rho g} + \frac{\overline{V}_D^{\,2}}{2g} + \Delta H_{CD}$$

Since the area ratio, inlet to outlet, of the diffuser is 1:4 the outlet kinetic head is 1/16 of the inlet kinetic head. For example if:

$h_A = 375$ mm $\quad h_B = 110$ mm $\quad h_C = 350$ mm $\quad h_D = 360$ mm

then: Inlet kinetic head = 44.26 mm

(See Venturi meter head loss calculations). The corresponding outlet kinetic head is:

$$\frac{44.26}{16} = 2.8 \text{ mm}$$

and

$$\Delta H_{CD} = (350 - 360) + (44.26 - 2.8) = 31.46 \text{ mm of water.}$$

Therefore

$$\text{Head Loss is } \frac{31.46}{44.26} = 0.71 \text{ inlet kinetic heads}$$

Right Angled Bend

The inlet to the bend is at (G) where the pipe bore is 51.9 mm and outlet is at (H) where the bore is 40 mm. Applying Equation (1):

$$\frac{p_G}{\rho g} + \frac{\overline{V}_G^{\,2}}{2g} = \frac{p_H}{\rho g} + \frac{\overline{V}_H^{\,2}}{2g} + \Delta H_{GH}$$

The outlet kinetic head is now 2.8 times the inlet kinetic head. For example if:

$h_A = 375$ mm $\quad h_B = 110$ mm
$h_G = 98$ mm $\quad h_H = 88$ mm

and

Inlet kinetic head = 2.76 mm
Outlet kinetic head = 7.73 mm

then

$$\Delta H_{GH} = (98 - 88) + (2.76 - 7.73) = 5.03 \text{ mm of water}$$

Therefore

$$\text{Head Loss is } \frac{5.03}{2.76} = 1.82 \text{ inlet kinetic heads}$$

Procedure:

1. Connect the supply hose from the hydraulic bench (H1 or H1D) to the inlet of the Venturi meter and secure with a hose clip. Connect a hose to the H10 control valve outlet and direct its free end into the hydraulic bench-measuring device. Before continuing, refer to the hydraulic bench manual to find the method of flow evaluation.

2. Make sure the air purge valve is closed. Close the H10 control valve fully, then open it by about 1/3. Switch on the hydraulic bench pump. Slowly open the hydraulic bench valve until water starts to flow. Allow the Flow Measurement apparatus to fill with water. Open the bench valve fully, and then close the H10 control valve. Connect the hand pump to the air purge valve and pump until all the manometers read approximately 330 mm. Dislodge any entrapped air from the manometers by gentle tapping with the fingers. Check that the water levels are constant. The levels will rise slowly if the purge valve is leaking.

3. Check that the tube ferrules and the top manifold are free from water blockage, which will suppress the manometer level. Blockages in the ferrules can be cleared by a sharp burst of pressure from the hand pump.

4. Open the apparatus valve until the rotameter shows a reading of approximately 10 mm. When a steady flow is maintained measure the flow with the Hydraulic Bench as outlined in its manual. During this period, record the readings of the manometers in Table 1.

5. Repeat this procedure for a number of equidistant values of rotameter readings up to the point in which the maximum pressure values can be recorded from the manometer.

		Test Number									
		1	2	3	4	5	6	7	8	9	10
	A										
	B										
Manometer Levels	C										
	D										
	E										
	F										
	G										
	H										
	I										
Rotameter (cm)											
Water *W* (kg)											
Time *T* (seconds)											
Mass Flow Rate m (kg/s)	Venturi										
	Orifice										
	Rotameter										
	Weigh Tank										
ΔH/Inlet Kinetic Head	Venturi										
	Orifice										
	Rotameter										
	Diffuser										
	Elbow										

Table 1: a blank results table

Discussion of the Meter Characteristics

There is little to choose in the accuracy of discharge measurement between the Venturi meter, the orifice meter and the rotameter. All are dependent upon the same principle. Discharge coefficients and the rotameter calibration are largely dependent on the way the stream from a 'vena contracta' or actual throat of smaller cross-sectional area than that of the containing tube. This effect is negligibly small where a controlled contraction takes place in a Venturi meter but is significant in the orifice meter. The orifice meter discharge coefficient is also dependent on the precise location of the pressure tappings (E) and (F). Such data is given in BS1042 which also emphasises the dependence of the meters behaviour on the uniformity of the flow upstream and downstream of the meter.

In order to keep the apparatus as compact as possible the dimensions of the equipment in the neighbourhood of the orifice meter have been reduced to their limit, consequently some inaccuracy in the assumed value of its discharge may be anticipated.

The considerable difference in head loss between the orifice meter and the Venturi meter should be noted. The orifice meter is much simpler to make and use, for it is comparatively easy to manufacture a suitable orifice plate and insert it between two existing pipe flanges which have been appropriately pressure-tapped for the purpose. In contrast the Venturi meter is large, comparatively difficult to manufacture and complicated to fit into an existing flow system. But the low head loss associated with the controlled expansion occurring in the Venturi meter gives it an obvious superiority in applications where power to overcome flow losses may be limiting.

Rotameters and other flow measuring instruments that depend on the displacement of floats in tapered tubes may be selected from a very wide range of specifications. They are unlikely to be comparable with the Venturi meter from the standpoint of head loss but, provided the discharge range is not extreme, the ease of reading the instrument may well compensate for the somewhat higher head loss associated with it.

The head losses associated with the wide-angled diffuser and the right-angled bend are typical. Both could be reduced if it were desirable to do so. The diffuser head loss would be minimized if the total expansion angle of about 50° were reduced to about 10°. The right-angled bend loss would be substantially reduced if the channel, through which water flows, were shaped in the arc of a circle having a large radius compared with the bore of the tube containing the fluid.

Large losses in internal flow systems are associated with uncontrollable expansion of the stream. Attention should always be paid to increases in cross-sectional area and changes of direction of the stream as these parts of the system are most responsive, in terms of associated head loss, to small improvement in design.

Discussion of Results

If the mass flow results are plotted against mass flow rates from the weighing tank method, the accuracy of the various methods can be compared. Since all are derived from Equation (1) similar results would be expected from the three methods. The differential mass flow measurement (m_{meter} - $m_{weightank}$) could be plotted against the weighing tank mass flow results for a better appraisal of accuracy.

Some overestimation in the Venturi meter termination can be anticipated because its vena contracta has been assumed to be negligibly small. Similarly, the rotameter determination may well be sensitive to the proximity of the elbow and the associated inlet velocity distribution. The orifice meter is likely to be sensitive to the inlet flow which is associated with the separation induced in the wide-angle diffuser upstream of it. Thus both the rotameter and the orifice meter calibrations would be likely to change if a longer length of straight pipe were introduced upstream of them.

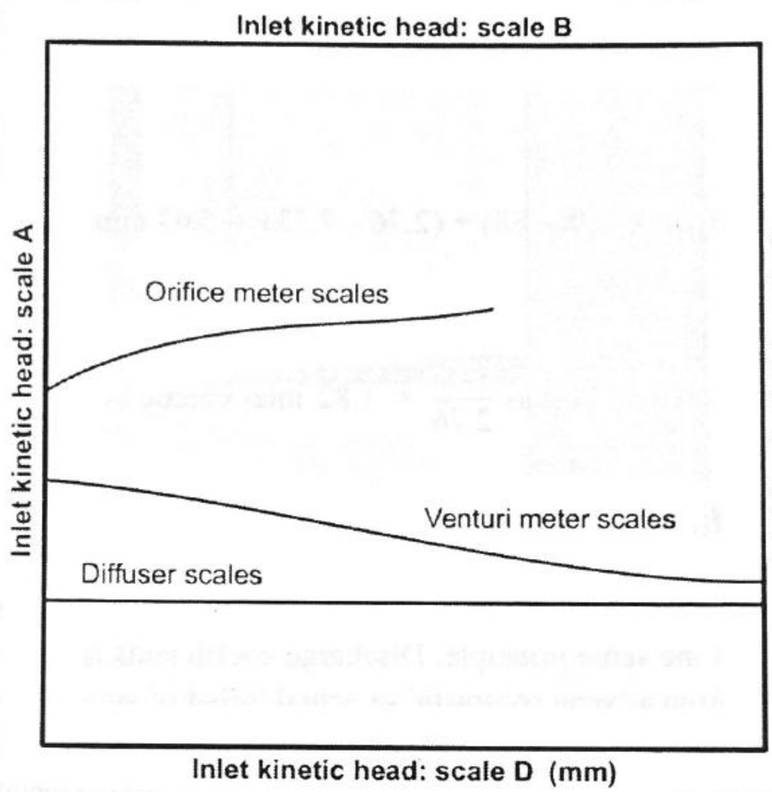


Fig. 9: typical head loss graph

In the calculations, the head losses associated with the various meters and flow components have been made dimensionless by dividing by the appropriate inlet kinetic heads. The advantage of the Venturi meter over the orifice meter and rotameter is evident, although over a considerable range of inlet kinetic heads the loss associated with the rotameter is sufficiently small to consider that it would be more than compensated by the relative ease in evaluation of mass flow from this instrument.

It should also be noted from figure 9 that the dimensionless head loss of the venturi meter and the orifice meter are renolds number dependent. This effect is also noticeable with the dimensionless head loss of the elbow

Questions for further discussion:

1. Which method is more accurate in measuring discharge? Explain.
2. Explain why the rotameter must have a slightly diverging cross – section?

Conclusion: does the objectives of the experiment achieved? How?