H10
Flow Measurement Apparatus

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CH/db/0810

TecQuipment

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SECTION 1.0 INTRODUCTION

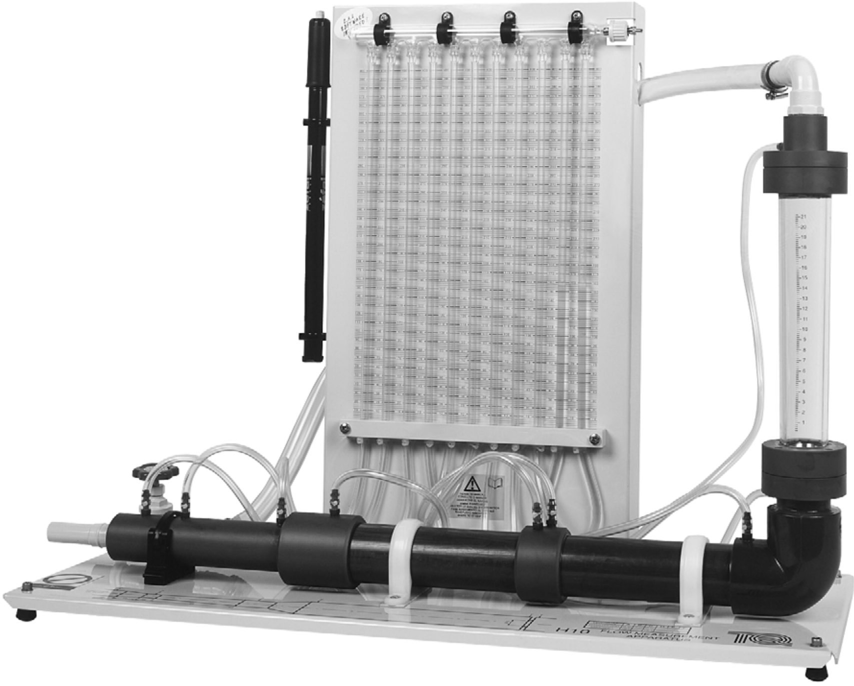

Figure 1 Flow Measurement Apparatus

The Flow Measurement apparatus (H10) familiarises students with the typical methods of measuring the discharge of an essentially incompressible fluid, whilst giving applications of the Steady-Flow Energy Equation and Bernoulli's Equation. The discharge is determined using a Venturi meter, an orifice plate meter and a rotameter. Head losses associated with each meter are determined and compared as well as those arising in a rapid enlargement and a 90° elbow.

The unit is for use with the TecQuipment Hydraulic Benches, H1 or H1D, which provide the necessary liquid service and evaluation of flow rate.

SECTION 2.0 DESCRIPTION OF THE APPARATUS

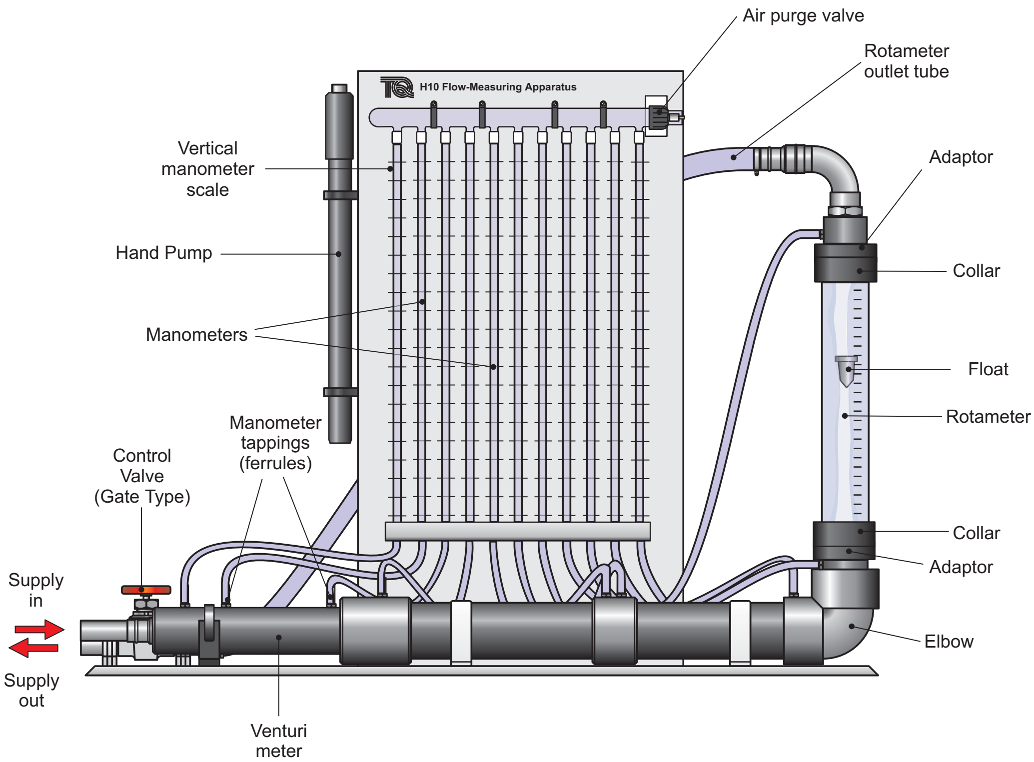

Figure 2 Flow Measurement Apparatus

Figure 2 shows the Flow Measurement apparatus. Water from the Hydraulic Bench enters the equipment through a Venturi meter, which consists of a gradually converging section, followed by a throat, and a long gradually diverging section. After a change in cross-section through a rapidly diverging section, the flow continues along a settling length and through an orifice plate meter. This is manufactured in accordance with BS1042, from a plate with a hole of reduced diameter through which the fluid flows. The H10 has eleven manometers, nine are connected to tappings in the pipework and two are left free for other measurements.

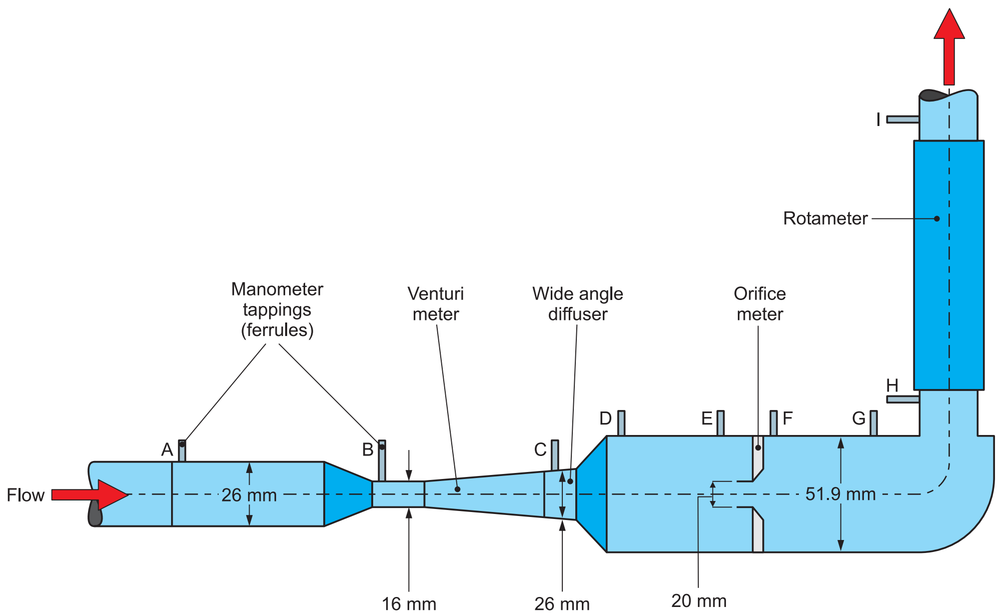

Figure 3 Explanatory Diagram of the Flow Measurement Apparatus

Installation

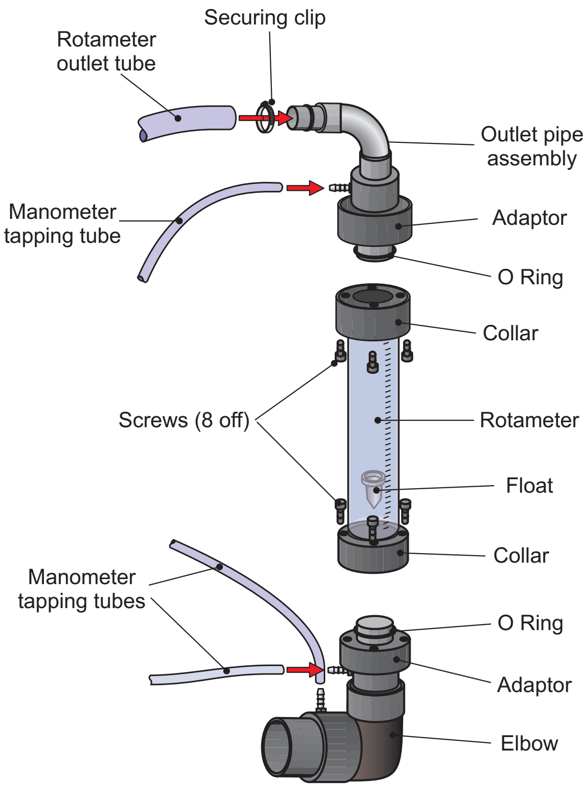

Figure 4 Rotameter Connection Diagram

Figure 4 shows the layout of the rotameter assembly. The Rotameter Tube is bonded to the two collars. The collars mate with the two adaptors and are held together with 8 screws (four on the upper collar and four on the lower collar).

To fit the rotameter and float:

CAUTION *The Rotameter tube is made of glass, take care not to break it.*

1. Make sure the O rings are correctly fitted to the adaptors.
2. Hold the Rotameter tube with the numbered scale the correct way up (highest numbers at the top).
3. Gently slide the bottom collar of the Rotameter over the O ring on the bottom adaptor.
4. Gently drop the float into the Rotameter tube (pointed end down).
5. Slide the top adaptor into the top collar of the Rotameter.
6. Secure the collars to the adaptors with the eight screws (supplied). Do not over tighten.
7. Attach the clear outlet tube, securing with the pipe clip.
8. Fit the manometer tapping tubes, securing with a cable tie.

Preparation

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.

Routine Care and Maintenance

Do not allow water to stand in the apparatus for long periods. After use fully drain the apparatus and dry externally with a lint-free cloth.

Control Valve

The control valve is a commercial gate valve, the internal details of which are shown in Figure 5. Slight gland leakage can be rectified as follows:

1. Remove the hand wheel retaining nut and the hand wheel.

2. Remove the securing nut. The gland packing ferrule will now be exposed. The head of the ferrule should be about 2 mm clear of the thread. If it is 2 mm or more, refit and tighten the securing nut. This should stop the leak. If the gap is less than 2 mm or there is no gap at all, replace the packing with 'o' rings.

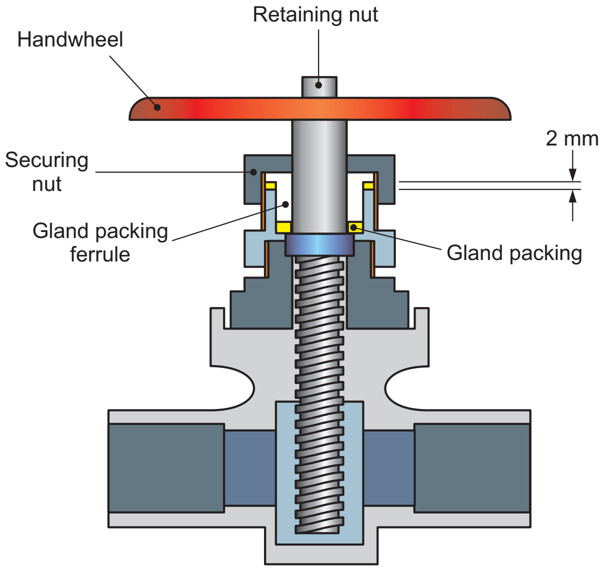

Figure 5 Internal Workings of a Gate Valve.

Manometer Tubes

If the plastic manometer tubes become discoloured, a stain and deposit remover is available for use within the bench supply.

SECTION 3.0 THEORY

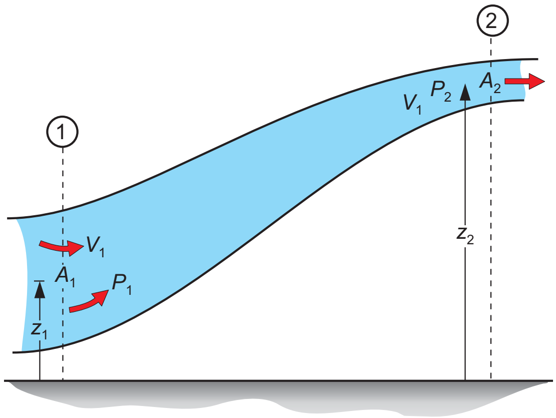

Figure 6 The Steady Flow energy equation

For steady, adiabatic flow of an incompressible fluid along a stream tube, as shown in Figure 6, Bernoulli's Equation can be written in the form:

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

Where:

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

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

z = Potential Head

$\frac{p}{\rho g} + \frac{\bar{V}^2}{2g} + z$ = 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.

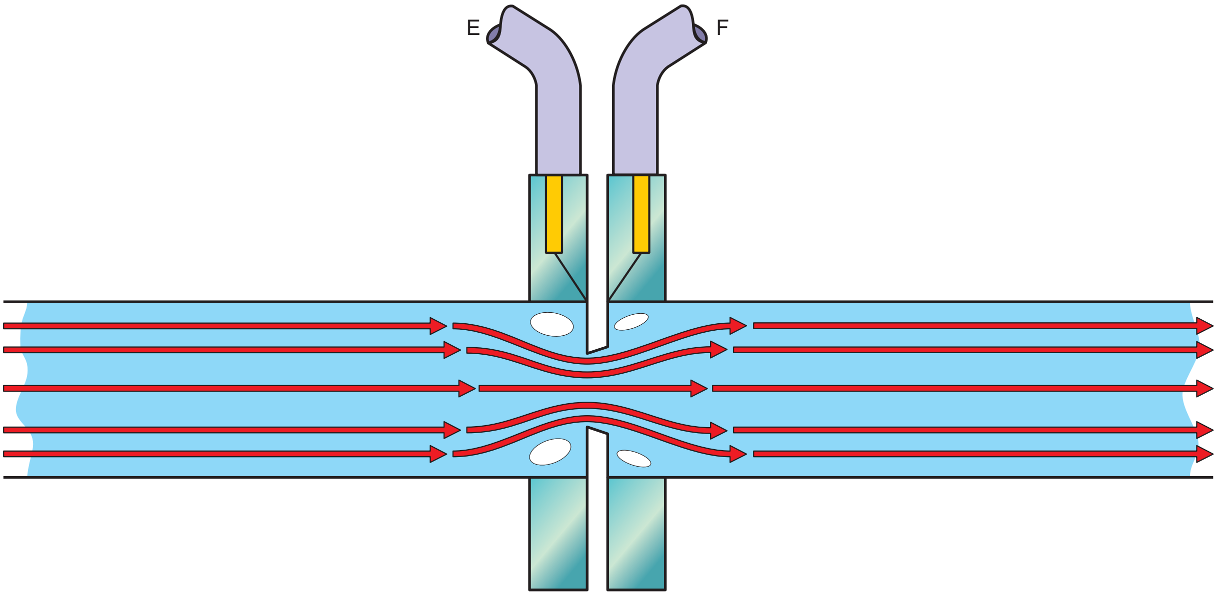

Figure 7 Construction of the Orifice meter.

SECTION 4.0 EXPERIMENTAL PROCEDURE

When the equipment has been set up as in Section 2, measurements can be taken in the following manner:

1. 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.

2. 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 Form of results.

SECTION 5.0 RESULTS AND CALCULATIONS

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.

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):

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

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

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

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

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

and

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

(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:

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

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:

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

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,

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

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

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

For example, if

h_E = 372 mm and

h_F = 40 mm,

then,

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

and

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

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

Rotameter

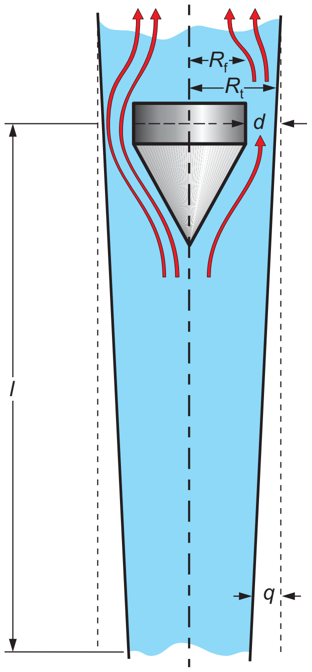

Figure 8 Principle of the Rotameter

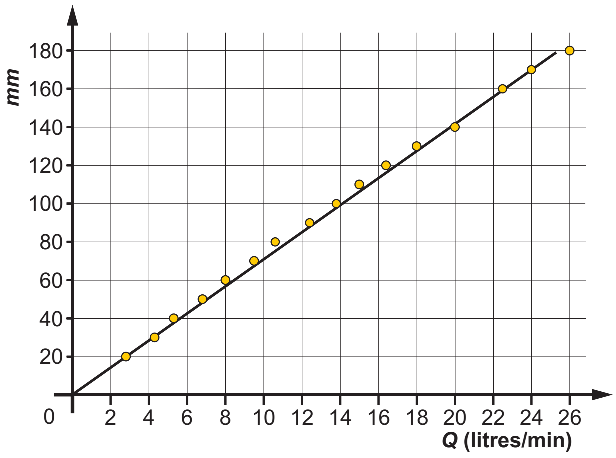

Figure 9 Typical Rotameter Calibration Curve

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 8, if the float radius is R_f and the local bore of the rotameter tube is $2R_t$ 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 9).

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 $\dfrac{\bar{V}_A{}^2}{2g}$.

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

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

$$= 44.26 \text{ mm}$$

Therefore,

$$\text{Head Loss} = \frac{25}{44.26} = 0.565 \text{ inlet kinetic heads}$$

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:

$$\Delta H_{\mathrm{EF}} = 0.83(h_{\mathrm{E}} - h_{\mathrm{F}})\ \mathrm{mm}$$

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

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:

$$\left(\frac{p_{\mathrm{H}}}{\rho g} + z_{\mathrm{H}}\right) - \left(\frac{p_{\mathrm{I}}}{\rho g} + z_{\mathrm{I}}\right) = \Delta H_{\mathrm{HI}}$$

Then, as illustrated in Figure 10:

$$h_{\mathrm{H}} - h_{\mathrm{I}} = \Delta H_{\mathrm{HI}}$$

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.

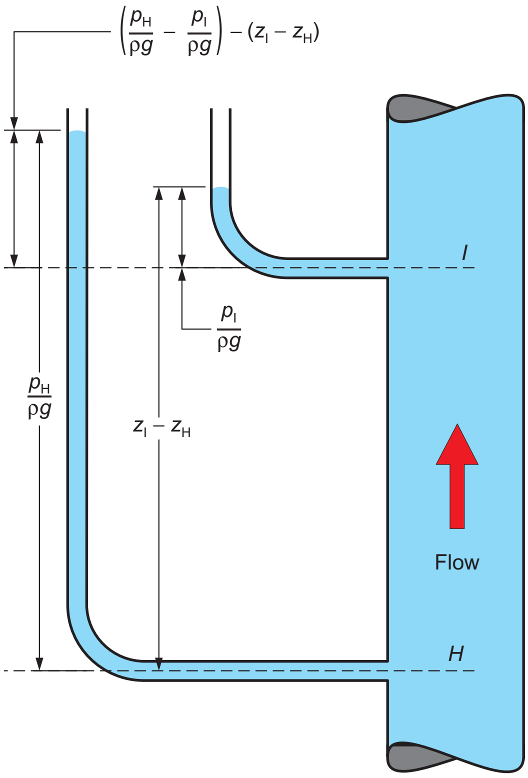

Figure 10 Rotameter Head Loss

Wide-Angled Diffuser

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

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

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 h_B = 110 mm h_C = 350 mm 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):

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

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

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

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.

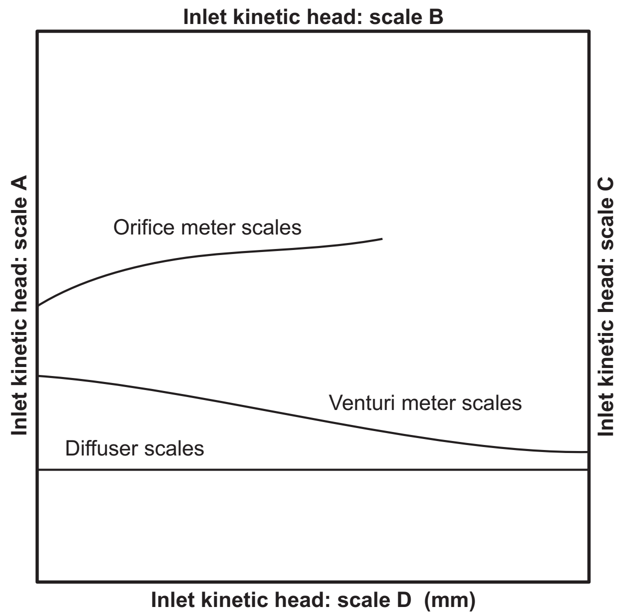

Figure 11 Typical Head Loss Graph

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 11 that the dimensionless head losses of the Venturi meter and the orifice meter are Reynolds number dependent. This effect is also noticeable with the dimensionless head loss of the elbow.

Conclusions

The most direct measurement of fluid discharge is the weigh tank principle. In installations where this is impracticable (e.g. on account of size of installation or gaseous fluid flow), one of the three discharge meters described may be used instead.

The Venturi meter offers the best control to the fluid. Its discharge coefficient is little different from unity and the head loss it offers is minimal. But it is relatively expensive to manufacture and could be difficult to install in existing pipework.

The orifice meter is easiest to install between existing pipe flanges and provided it is manufactured and erected in accordance with BS1042, will give accurate measurement. The head loss associated with it is very large compared with that of the Venturi meter.

The rotameter gives the easiest derivation of discharge, dependent only on sighting the float and reading a calibration curve. It needs to be chosen wisely, however, so that the associated head loss is not excessive.

TecQuipment

Air Valves

TecQuipment's

Fluid Mechanics Products

Instruction Sheets

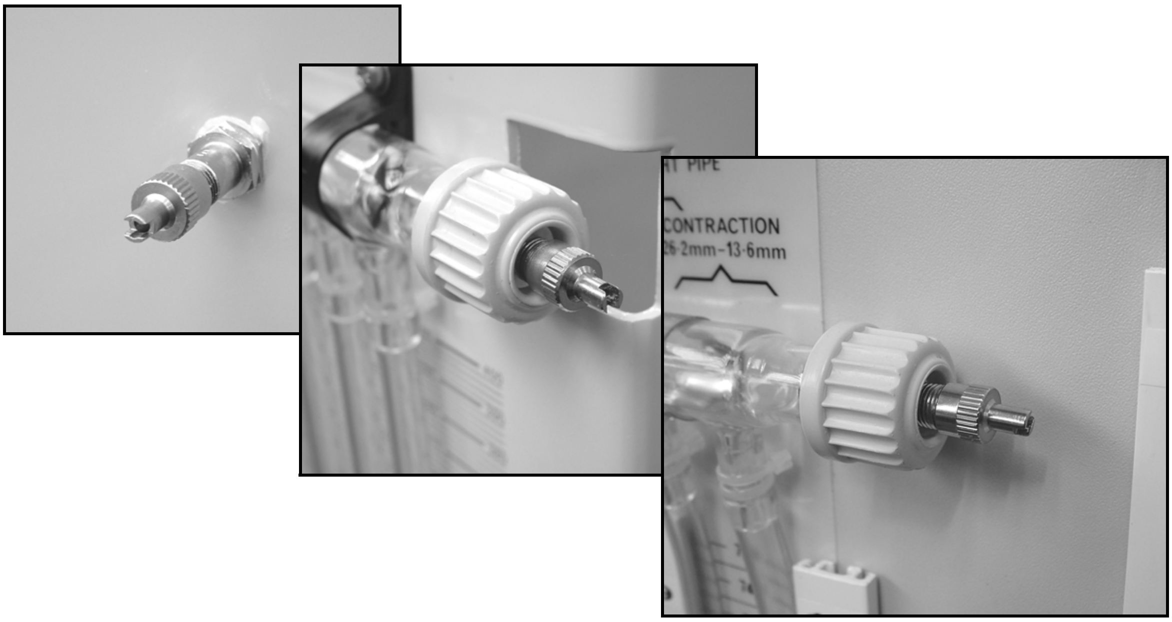

Figure 12 Typical Air Valves on Some of TecQuipment's Products

Many of the products in TecQuipment's Fluid Mechanics range use air valves at the tops of manometers or piezometers. The valves keep the air in the manometer tubes to allow you to offset the pressure range of the manometer or piezometer.

The valves are similar to valves used in vehicle tyres and include a special cap. The hand pump supplied with the equipment is similar to those used for bicycle tyres, except that TecQuipment remove the cross-shape part of the flexible pipe.

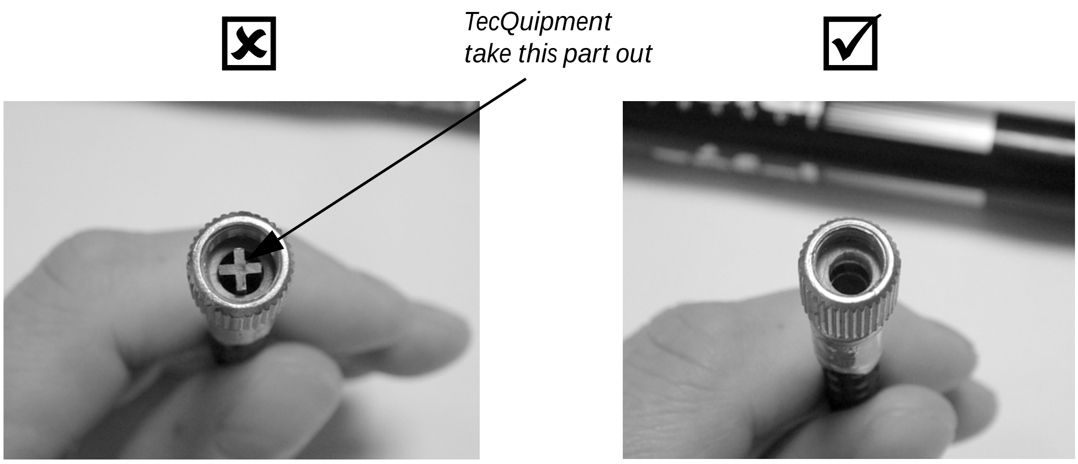

Figure 13 TecQuipment Remove the Cross-shape Part of the Flexible Pipe

Normally, when you connect the flexible pipe to an air valve, the cross-shape piece in the flexible pipe pushes open the valve as you pump air with the hand pump. With TecQuipment fluid mechanics products, this could allow water back out through the valve. For this reason TecQuipment remove the cross-shape piece. Without the cross-shape piece, only pressurised air can go through the valve in one direction, and no water can come back out.

Figure 14 The Hand Pump and Flexible Pipe

When you first use the hand pump with the air valve, you may find it hard to push air through the valve. This is because the valve is new and you do not have the cross-shape piece to help push it open. The valve will open more easily after you have pumped air through it a few times.

You may need some practice to use the air valve. To do it correctly:

1. Unscrew the cap from the valve.

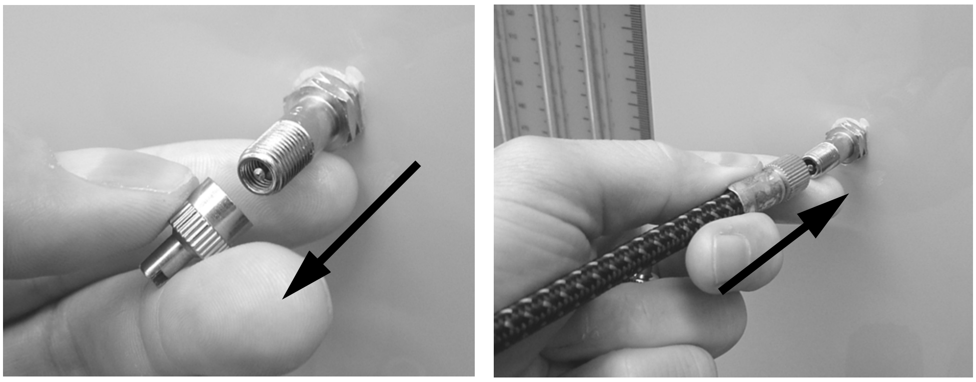

Figure 15 Unscrew the Cap and Fit the Pipe

2. Connect the flexible pipe to the valve.

3. Connect the hand pump to the flexible pipe.

4. Using complete strokes, ***slowly and firmly*** pump the hand pump to force air into the manometer or piezometer.

5. Unscrew the hand pump and flexible pipe and refit the valve cover.

6. To let air back out through the air valve, use the end of the special cap to press on the inner part of the valve (see Figure 16).

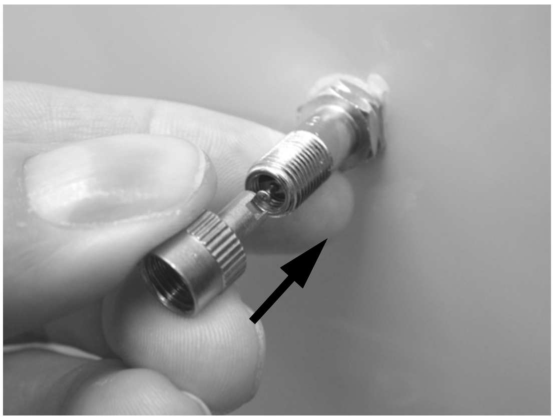

Figure 16 To Let Air Out - Use the End of the Special Cap to Press the Inner Part of the Valve

WARNING

Take care when you let air back out from the air valve. Water may come out!

Clean up any water spills immediately.

If using the hand pump is too difficult, the valve may be stuck. If you need to check the valve is working, use the special cap to unscrew the valve, then gently press the end of the valve. It should move easily and return back to its original position (see Figure 17).

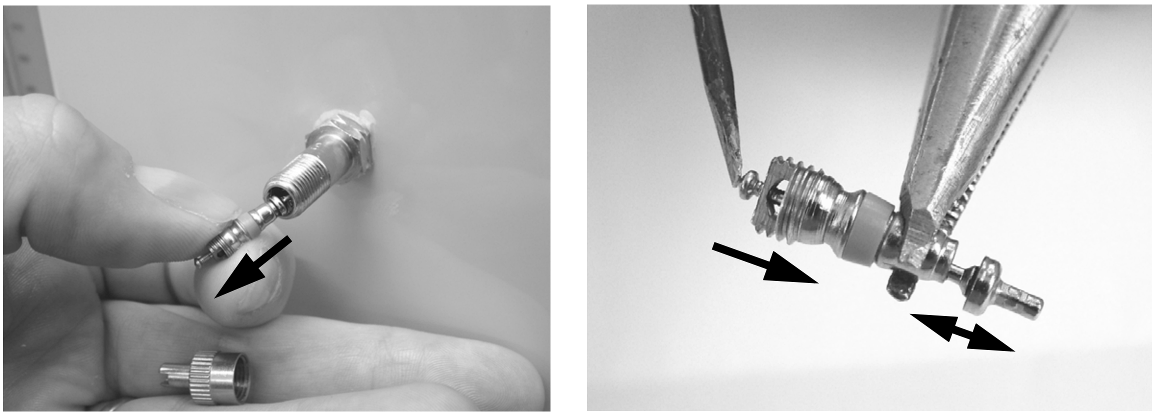

Figure 17 Unscrew the Valve and Check it

If the valve does not move easily, then contact TecQuipment Customer Services for help.

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Email: customer.care@tecquipment.com

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