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# The design of piezometer rings

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A mathematical model is developed with which the reading from a piezometer ring may be predicted from the individual wall static measurements and from this the conventional form of ring is shown to be unreliable in asymmetrical flow. An alternative form of ring known as the Triple-T is analysed and shown to provide a true mean pressure in all cases. It is recommended that this form be used in all future test work. Tests demonstrating the validity of the theory are described.

## 1. Introduction

The piezometer ring is widely used in the field of flow measurement yet its behaviour is little understood. It is normally used as a means of providing an 'average' pressure reading from four or more static pressure tappings equally spaced round the circumference of a pipe or flowmeter. In some tests it is standard procedure to compare a ring reading with readings from the individual tappings and normally the ring 'average' proves to be satisfactory. When one tapping reading differs significantly from the others it is blocked off on the grounds that the hole has been incorrectly drilled, and the others are combined to give the ring reading. Under normal calibration conditions this is probably a valid assumption but it must be approached with caution in circumstances where the flow might be asymmetric. A model is developed here which allows the pressure at any point in a piezometer ring to be deduced from the individual tapping readings; it is worked out specifically for four tappings but can be extended to any number. The model is also used to determine the most suitable method of combining individual tappings into a piezometer ring in order to measure the mean pressure accurately.

## 2. Fluid dynamics of the piezometer ring

Figure 1 represents a normal, conventional piezometer ring. In general, if the pressures $P_1$, $P_2$, $P_3$ and $P_4$ are all different there will be a flow into or out of each tapping and a flow in each section of the ring. The only limb in which the fluid will be at rest in steady-state conditions is the one leading to the manometer or other pressure-sensing device. Hence there is a dynamic interaction amongst the pressures, which complicates calculation of the ring pressure at any point.

Consider now an element of pipe (which may be the tubing of which the ring is constructed or indeed the wall tapping itself) containing a steady flow of

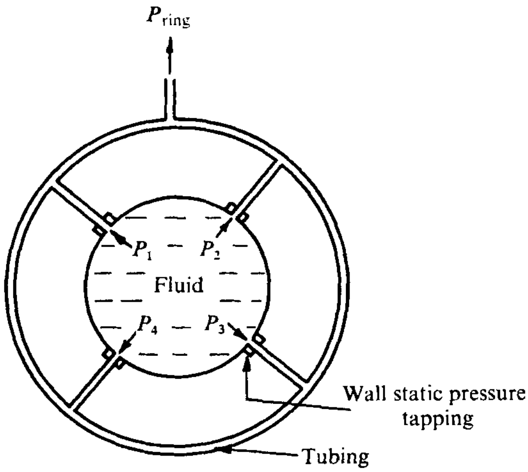


FIGURE 1. Piezometer ring.

incompressible fluid. A force balance may be written as follows:

$$-\left(\frac{dP}{dL}\right) dL \frac{\pi D^2}{4} = \tau_w \pi D\, dL, \tag{1}$$

where $D$ is the pipe diameter, $dL$ is the length of the element, $P$ is the pressure and $\tau_w$ is the wall shear stress. Hence

$$dP/dL = -4\tau_w/D. \tag{2}$$

Now $\tau_w$ is proportional to the kinetic energy per unit volume of the fluid, so (2) may be rewritten as

$$dP/dL = -f 2\rho V^2/D, \tag{3}$$

where $V$ is the average velocity in the pipe and $f$ is known as the friction factor. Below a Reynolds number $Re$ of about 2000, $f$ is easily shown to be given by

$$f = 16/Re. \tag{4}$$

Hence

$$\frac{dP}{dL} = \frac{-16\nu}{VD}\frac{2\rho V^2}{D} = \left(\frac{-32\rho\nu}{D^2}\right) V, \tag{5}$$

where $\rho$ is the fluid density and $\nu$ the kinematic viscosity. Combining the terms in the bracket to form a constant $C$ and incorporating the minus sign for convenience, one may write

$$\Delta P = C \Delta L V \quad \text{or} \quad \Delta P = R'V, \tag{6),(7}$$

where $R'$ is a resistance factor directly proportional to the length of pipe and inversely proportional to its area. Alternatively, since the volume flow rate $Q$ is the cross-sectional area multiplied by the average velocity, one may write more generally

$$\Delta P = \frac{-32\rho\nu}{D^2}\frac{4Q}{\pi D^2}\Delta L \quad \text{or} \quad \Delta P = RQ, \tag{8),(9}$$

which is more directly analogous to the electrical case:

$$E = RI, \tag{10}$$

where $I$ is a current and $E$ is a voltage drop.

The above remarks apply exactly only in the case of steady, developed, incompressible flow in straight sections where the flow rate is sufficiently low to remain laminar. However this is a reasonable approximation in almost all cases of relevance.

## 3. The network model

It was shown in § 2 that the pressure losses in the components of a piezometer ring can normally be represented by *linear* resistances. Thus the electrical analogy is pressure equivalent to voltage, flow rate equivalent to current and the factor $R$ equivalent to resistance, and the simplest form of linear network analysis can be used to solve the steady state. Figure 2 shows the equivalent electrical circuit. Because the resistances are being treated as linear, the individual contributions in, say, a leg of the ring, including hole, tubing and perhaps a stopcock or other fitting, need not be known explicitly, but can be considered together as a single resistance.

The first step in the solution is to redraw the circuit so that the connexions can be seen clearly and the nodal points determined. There are five nodes, eight branches and four independent loops. These are assigned labels and directions as shown in figure 3.

Now the connexion matrix $\mathbf{C}$ which links the eight branch flows to the four independent loop flows must be formed. From inspection of figure 3,

$$\left.\begin{aligned} q_a = q_1 - q_4, \quad q_b = q_2 - q_1, \quad q_c = q_3 - q_2, \quad q_d = q_4 - q_3, \\ q_e = q_1, \quad q_f = q_2, \quad q_g = q_3, \quad q_h = q_4 \end{aligned}\right\} \tag{11}$$

and

$$\mathbf{q} = \mathbf{C}\mathbf{q}', \tag{12}$$

where $\mathbf{q}$ and $\mathbf{q}'$ are column vectors with components $q_a, \ldots, q_h$ and $q_1, \ldots, q_4$ respectively,

so

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & -1 \\ -1 & 1 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 0 & -1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{13}$$

The vector $\mathbf{P}'$ of the driving pressures is found by inspecting the pressures in each loop:

$$\mathbf{P}' = \begin{bmatrix} P_1 - P_2 \\ P_2 - P_3 \\ P_3 - P_4 \\ P_4 - P_1 \end{bmatrix} \tag{14}$$

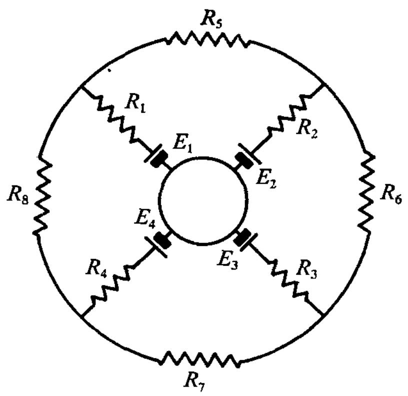


FIGURE 2. Electrical analogue of piezometer ring.

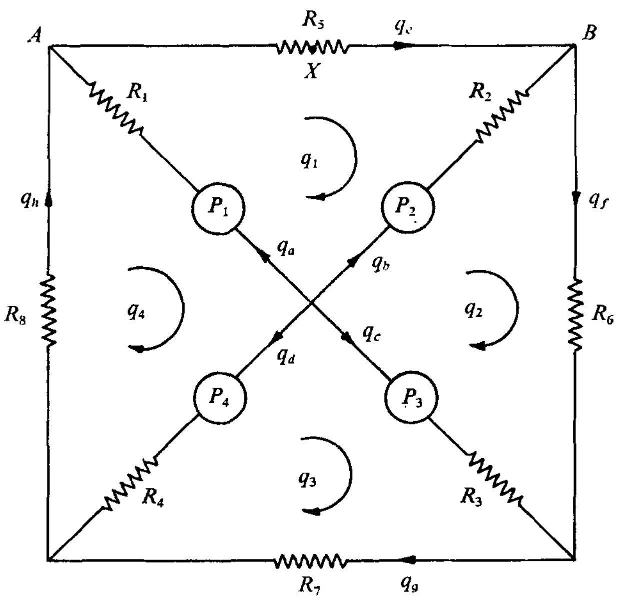


FIGURE 3. Network diagram showing the branch flows $q_a, \ldots, q_h$ and their directions and the independent mesh flows $q_1, \ldots, q_4$.

For the simple case of linear resistances, all entries in the impedance matrix are zero except along the main diagonal:

$$\mathbf{R} = \begin{bmatrix} R_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & R_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & R_3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & R_4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & R_6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & R_7 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_8 \end{bmatrix} \tag{15}$$

$\mathbf{P}'$ and $\mathbf{R}$ are linked by the equation

$$\mathbf{P}' = \mathbf{C}^{\mathrm{T}}\mathbf{R}\mathbf{C}\mathbf{q}', \tag{16}$$

where $\mathbf{C}^{\mathrm{T}}$ is the transpose of $\mathbf{C}$. This is equation (9) in more general form. Thus

$$\mathbf{P}' = \begin{bmatrix} 1 & -1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 1 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{bmatrix} \mathbf{R}\mathbf{C}\mathbf{q}'$$

$$= \begin{bmatrix} R_1 & -R_2 & 0 & 0 & R_5 & 0 & 0 & 0 \\ 0 & R_2 & -R_3 & 0 & 0 & R_6 & 0 & 0 \\ 0 & 0 & R_3 & -R_4 & 0 & 0 & R_7 & 0 \\ -R_1 & 0 & 0 & R_4 & 0 & 0 & 0 & R_8 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & -1 \\ -1 & 1 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 0 & -1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \mathbf{q}'$$

$$= \begin{bmatrix} R_1+R_2+R_5 & -R_2 & 0 & -R_1 \\ -R_2 & R_2+R_3+R_6 & -R_3 & 0 \\ 0 & -R_3 & R_3+R_4+R_7 & -R_4 \\ -R_1 & 0 & -R_4 & R_1+R_4+R_8 \end{bmatrix} \mathbf{q}'. \tag{17}$$

Let the $4 \times 4$ matrix in (17) be called $\mathbf{A}$. Then

$$\mathbf{q}' = \mathbf{A}^{-1}\mathbf{P}', \tag{18}$$

where $\mathbf{A}^{-1}$ is the inverse of $\mathbf{A}$. The solution of (18) allows all the pressures and flows to be calculated.

## 4. Sample calculations

Three cases are examined to indicate the overall behaviour of the system:

(*a*) $R_1 = R_2 = R_3 = R_4 = R_5 = R_6 = R_7 = R_8 = R$,

(*b*) $R_{1,2,3,4} \gg R_{5,6,7,8}$,

(*c*) $R_{1,2,3,4} \ll R_{5,6,7,8}$.

Case (*a*) corresponds to a system where the bore of the connecting tubing is the same as the diameter of the wall tappings and where the four legs from the tappings to the ring are all the same length and are also the same length as the four sections of the ring. Case (*b*) is the most common and would normally cover small diameter tappings which are very restrictive in comparison with the tubing. Case (*c*) rarely occurs, but might apply to a ring which closely fitted a large diameter pipe in which large wall tappings have been drilled.

In each case the pressure at the point in the piezometer ring from which the connexion to the manometer is taken (point $X$ in figure 3) is calculated.

*Case* (*a*). *Equal resistances.* Equation (17) gives

$$\mathbf{A} = R\begin{bmatrix} 3. & -1 & 0 & -1 \\ -1 & 3 & -1 & 0 \\ 0 & -1 & 3 & -1 \\ -1 & 0 & -1 & 3 \end{bmatrix}. \tag{19}$$

Hence

$$\mathbf{A}^{-1} = \frac{1}{R}\begin{bmatrix} 0{\cdot}467 & 0{\cdot}200 & 0{\cdot}133 & 0{\cdot}200 \\ 0{\cdot}200 & 0{\cdot}467 & 0{\cdot}200 & 0{\cdot}133 \\ 0{\cdot}133 & 0{\cdot}200 & 0{\cdot}467 & 0{\cdot}200 \\ 0{\cdot}200 & 0{\cdot}133 & 0{\cdot}200 & 0{\cdot}467 \end{bmatrix}. \tag{20}$$

So from (18) and (14)

$$\left.\begin{aligned} Rq_1 &= 0{\cdot}467P_{12} + 0{\cdot}200P_{23} + 0{\cdot}133P_{34} + 0{\cdot}200P_{41}, \\ Rq_2 &= 0{\cdot}200P_{12} + 0{\cdot}467P_{23} + 0{\cdot}200P_{34} + 0{\cdot}133P_{41}, \\ Rq_3 &= 0{\cdot}133P_{12} + 0{\cdot}200P_{23} + 0{\cdot}467P_{34} + 0{\cdot}200P_{41}, \\ Rq_4 &= 0{\cdot}200P_{12} + 0{\cdot}133P_{23} + 0{\cdot}200P_{34} + 0{\cdot}467P_{41}, \end{aligned}\right\} \tag{21}$$

where $P_{12} = P_1 - P_2$, etc. It may not always be necessary to write down all four equations (21) to obtain the desired information. Assume now that the ring pressure is measured at the point $X$, midway between the points $A$ and $B$ in figure 3. The pressure $P_A$ at $A$ is given by

$$P_A = P_1 + (q_4 - q_1)R_1, \tag{22}$$

i.e.

$$P_A = 0{\cdot}467P_1 + 0{\cdot}200P_2 + 0{\cdot}133P_3 + 0{\cdot}200P_4. \tag{23}$$

Similarly

$$P_B = 0{\cdot}200P_1 + 0{\cdot}467P_2 + 0{\cdot}200P_3 + 0{\cdot}133P_4,$$

$$P_X = \tfrac{1}{2}(P_A + P_B),$$

i.e.

$$P_X = 0{\cdot}333P_1 + 0{\cdot}333P_2 + 0{\cdot}167P_3 + 0{\cdot}167P_4. \tag{24}$$

The same answer may be arrived at by adding to $P_A$ the pressure drop between $A$ and $X$, which is $0{\cdot}5q_1R_5$.

Thus in the equal-resistance case the two tappings closest to the manometer lead are twice as important as the others.

*Case* (*b*). $R_{1,2,3,4}$ *large*. Take

$$R_1 = R_2 = R_3 = R_4 = 10R \quad \text{and} \quad R_5 = R_6 = R_7 = R_8 = R.$$

Then

$$\mathbf{A} = R\begin{bmatrix} 21 & -10 & 0 & -10 \\ -10 & 21 & -10 & 0 \\ 0 & -10 & 21 & -10 \\ -10 & 0 & -10 & 21 \end{bmatrix}, \tag{25}$$

$$\mathbf{A}^{-1} = \frac{1}{R}\begin{bmatrix} 0{\cdot}280 & 0{\cdot}244 & 0{\cdot}232 & 0{\cdot}244 \\ 0{\cdot}244 & 0{\cdot}280 & 0{\cdot}244 & 0{\cdot}232 \\ 0{\cdot}232 & 0{\cdot}244 & 0{\cdot}280 & 0{\cdot}244 \\ 0{\cdot}244 & 0{\cdot}232 & 0{\cdot}244 & 0{\cdot}280 \end{bmatrix}, \tag{26}$$

hence

$$P_A = 0{\cdot}280P_1 + 0{\cdot}244P_2 + 0{\cdot}232P_3 + 0{\cdot}244P_4, \tag{27}$$

and

$$P_X = 0{\cdot}262P_1 + 0{\cdot}262P_2 + 0{\cdot}238P_3 + 0{\cdot}238P_4.$$

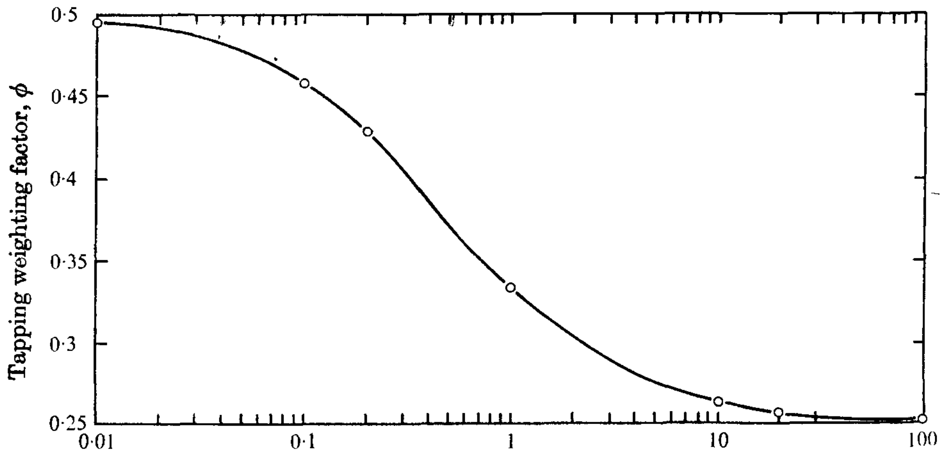


FIGURE 4. Variation of tapping weighting factor with resistance ratio.

Thus when the 'leg' resistances are relatively large the ring reading is again a fairly poor approximation to the true mean value, although it is closer to the average of the four pressures than in case (*a*).

*Case* (*c*). $R_{5,6,7,8}$ *large*. Take

$$R_1 = R_2 = R_3 = R_4 = R \quad \text{and} \quad R_5 = R_6 = R_7 = R_8 = 10R.$$

Then

$$\mathbf{A} = R\begin{bmatrix} 12 & -1 & 0 & -1 \\ -1 & 12 & -1 & 0 \\ 0 & -1 & 12 & -1 \\ -1 & 0 & -1 & 12 \end{bmatrix}, \tag{28}$$

$$\mathbf{A}^{-1} = \frac{1}{R}\begin{bmatrix} 0{\cdot}0845 & 0{\cdot}0071 & 0{\cdot}0012 & 0{\cdot}0071 \\ 0{\cdot}0071 & 0{\cdot}0845 & 0{\cdot}0071 & 0{\cdot}0012 \\ 0{\cdot}0012 & 0{\cdot}0071 & 0{\cdot}0845 & 0{\cdot}0071 \\ 0{\cdot}0071 & 0{\cdot}0012 & 0{\cdot}0071 & 0{\cdot}0845 \end{bmatrix}, \tag{29}$$

hence

$$P_X = 0{\cdot}458P_1 + 0{\cdot}458P_2 + 0{\cdot}042P_3 + 0{\cdot}042P_4. \tag{30}$$

In this case only the two tappings nearest to the manometer lead make a significant contribution to the ring reading.

*General case*. Figure 4 shows the relationship between the resistance ratio $R_1/R_5$ (where $R_1 = R_2 = R_3 = R_4$ and $R_5 = R_6 = R_7 = R_8$) and the tapping weighting factor $\phi$. For symmetrical rings, the ring pressure $P_X$ is given by

$$P_X = \phi(P_1+P_2) + (0{\cdot}5-\phi)(P_3+P_4),$$

where $P_1$ and $P_2$ are the two nearest tappings. To minimize the likelihood of a significant error in the mean value measured this resistance ratio should be as high as possible.

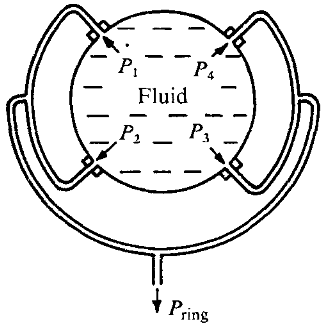


FIGURE 5. Triple-T ring.

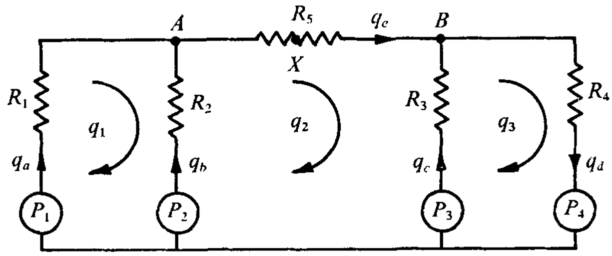


FIGURE 6. Network diagram for Triple-T ring.

## 5. The Triple-T ring

An alternative form of ring, used for many years in the Flow Measurement Division of NEL, is shown in figure 5. It was introduced originally as a means of reducing the number of T connectors required on rigs where many were in use. It was thoroughly tested before being instituted and was found to provide a satisfactory average pressure reading. An analysis of this form of ring follows.

From inspection of the equivalent network diagram of the Triple-T ring (figure 6),

$$q_a = q_1, \quad q_b = q_2 - q_1, \quad q_c = q_3 - q_2, \quad q_d = q_3, \quad q_e = q_2, \tag{31}$$

thus in (12)

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \tag{32}$$

and with

$$\mathbf{R} = \begin{bmatrix} R_1 & 0 & 0 & 0 & 0 \\ 0 & R_2 & 0 & 0 & 0 \\ 0 & 0 & R_3 & 0 & 0 \\ 0 & 0 & 0 & R_4 & 0 \\ 0 & 0 & 0 & 0 & R_5 \end{bmatrix}$$

(16) becomes

$$\mathbf{P}' = \begin{bmatrix} P_1 - P_2 \\ P_2 - P_3 \\ P_3 - P_4 \end{bmatrix} = \mathbf{C}^{\mathrm{T}}\mathbf{R}\mathbf{C}\mathbf{q}',$$

or

$$\mathbf{P}' = \begin{bmatrix} R_1 + R_2 & -R_2 & 0 \\ -R_2 & R_2 + R_3 + R_5 & -R_3 \\ 0 & -R_3 & R_3 + R_4 \end{bmatrix} \mathbf{q}'. \tag{33}$$

This may be solved immediately, with the usual assumption that

$$R_1 = R_2 = R_3 = R_4 = R$$

and $R_5$ is unspecified. Then

$$\left.\begin{aligned} P_{12} &= 2Rq_1 - Rq_2, \\ P_{23} &= -Rq_1 + (2R + R_5)\,q_2 - Rq_3, \\ P_{34} &= -Rq_2 + 2Rq_3. \end{aligned}\right\} \tag{34}$$

The measured pressure is $P_X = \frac{1}{2}(P_A + P_B)$. Now

$$P_A = P_2 + R(q_1 - q_2), \quad P_B = P_3 + R(q_2 - q_3),$$

hence

$$P_X = \tfrac{1}{2}\{P_2 + P_3 + R(q_1 - q_3)\}. \tag{35}$$

From (34)

$$P_{12} - P_{34} = 2Rq_1 - 2Rq_3,$$

and hence

$$P_X = \tfrac{1}{4}(2P_2 + 2P_3 + P_1 - P_2 - P_3 + P_4),$$

that is

$$P_X = \tfrac{1}{4}(P_1 + P_2 + P_3 + P_4) \tag{36}$$

and this form of ring gives a true average reading under all circumstances, independent of the value of $R_5$.

## 6. Experimental verification

*Simulation of piezometer ring*

In most normal circumstances, any discrepancies predicted by the theory will be small. Therefore it was decided to attempt to verify the theory in an extreme case of asymmetry. The simplest way of obtaining steady but widely differing wall static readings was to use four tappings in line down a straight section of pipe. These were connected in various ways to form the rings. Nylon tubing of 4 mm ($\frac{5}{32}$ in.) bore and appropriate Simplifix fittings were used thoughout. Pressures were read from an inverted air-over-water manometer, using a fifth downstream tapping as a reference.

The dominant factor in the behaviour of the normal ring is the ratio of the total resistances in the leg (from hole to ring) to the resistances in each section of the ring itself. This ratio was varied in two ways. First, the holes were initially drilled to be 0·4 mm then were redrilled after testing to 1·6 mm, 3·18 mm and 4 mm in turn. Second, two sizes of ring were used to vary the ratio. The first had a leg length of 800 mm and a ring section length of 245 mm. The second had a leg length of 210 mm and a ring section length of 1165 mm. In each case a stopcock was included in the leg. Brief tests were also carried out on the effect of placing the lead from the ring off-centre. Finally the Triple-T was tested.

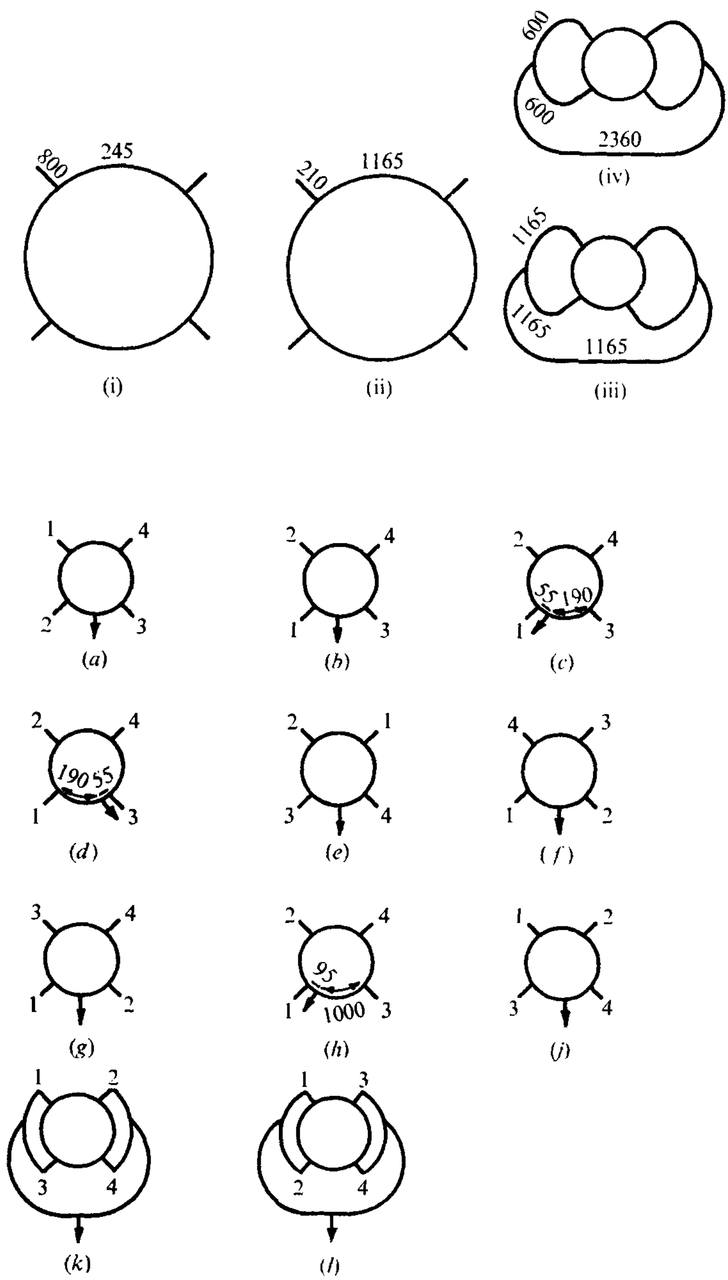


FIGURE 7. Key to ring configurations (dimensions where given are in mm).

*Accuracy and repeatability of measurements*

The pressure losses down the pipe and the spacing of the tappings were such that low flow rates had to be used to keep the pressure differentials within the manometer's range. This made it impossible to reset a particular flow rate with much better than 5 % accuracy. A turbine meter was used to set the flow rate and it was read at each test point to ensure that the flow rate remained steady for most of the tests.

The fluctuations of fluid level in the manometer limbs varied slightly with flow rate and with the tapping or ring being tested. For all cases the uncertainty associated with each differential pressure reading may be taken as not exceeding $\pm 3$ mm, thus when four individual tapping readings are measured there is an uncertainty in their mean value of $\pm 1{\cdot}5$ mm. When this is compared with a ring reading, the overall uncertainty in the discrepancy may be taken as approximately 3·5 mm or a little under 1 % at the flow rate used for most of the tests.

## *Results*

The results of these tests are given in table 1, with the key to the ring configurations shown in figure 7. Test 1 was the only one made with the extremely small hole size of 0·4 mm. The ring reading agreed with the true mean to within the experimental uncertainties. The resistance ratio may be calculated very roughly from (8) bearing in mind the approximations involved. Let the resistance of a 1 mm length of 4 mm bore tubing be unity. Then the hole resistance (length 3 mm) is $3 \times (4/0{\cdot}4)^4 \simeq 3 \times 10^4$. The resistance ratio is then greater than $10^2:1$ and the result is in accord with the prediction in that $R_1/R_5$ is large and the discrepancy small.

Tests 2–5 involved 1·6 mm holes. Tests 2 and 3 used straightforward rings and the agreement was again within the experimental uncertainties. Tests 4 and 5 had the manometer lead off-centre. Test 4, where the lead was close to a tapping with a high pressure, had the largest positive error of the set, and in test 5 the proximity of a tapping with a low pressure led to the only negative error. For a normal-sized standard ring this hole size should be regarded as the largest acceptable one for asymmetric flow as the disagreement is comparable with the measurement uncertainties.

Tests 6 and 7 had 3·18 mm holes, a size frequently used in test work. A resistance ratio of about 4 was expected and significant errors should appear. With the lead situated between the two tappings with the lowest pressures, the discrepancy was $-2{\cdot}7$ %, while it was $+2{\cdot}5$ % with the highest pressures.

In tests 8–10 the same holes were involved but were connected to a larger ring. The resistance ratio should be much smaller, perhaps below unity, and the discrepancies substantial. In fact disagreement of around 7 % was found, which implies a ratio of about 2:1, perhaps due to the resistance of the stopcock and associated fittings in the leg.

In test 11 the hole size was the same as the bore of the tubing, and the configuration was the same as in test 8. The discrepancy increased to about 10 %.

Test 12 involved the same large hole size as test 11 but a Triple-T configuration was used. The discrepancy was within the experimental errors.

A further Triple-T ring was then constructed and a series of tests carried out. These gave discrepancies of between $-1{\cdot}6$ and $-2{\cdot}3$ % of the mean values. It was concluded that there was a fault in the construction of the ring, for example that one of the Simplifix connexions had been overtightened, thus distorting the tubing. The increased resistance in that limb would cause that tapping to

| Test | Hole size | Configuration (see figure 7) | Tapping number | Static pressure (mm $H_2O$) | Mean of tappings $M$ (mm $H_2O$) | Ring reading $R$ (mm $H_2O$) | Discrepancy $100\left(\frac{R-M}{M}\right)$ (%) |
|---|---|---|---|---|---|---|---|
| 1 | 0·4 mm (0·016 in.) | i(*a*) | 1 | 651 | 444 | 439 | −1·1 |
| | | | 2 | 515 | | | |
| | | | 3 | 369 | | | |
| | | | 4 | 241 | | | |
| 2 | 1·6 mm (0·0625 in.) | i(*b*) | 1 | 700 | 451 | 456 | +1·1 |
| | | | 2 | 527 | | | |
| | | | 3 | 369 | | | |
| | | | 4 | 207 | | | |
| 3 | 1·6 mm | i(*a*) | 1 | 695 | 449 | 451 | +0·5 |
| | | | 2 | 526 | | | |
| | | | 3 | 368 | | | |
| | | | 4 | 206 | | | |
| 4 | 1·6 mm | i(*c*) | 1 | 687 | 468 | 474 | +1·3 |
| | | | 2 | 542 | | | |
| | | | 3 | 389 | | | |
| | | | 4 | 253 | | | |
| 5 | 1·6 mm | i(*d*) | 1 | 700 | 477 | 476 | −0·2 |
| | | | 2 | 553 | | | |
| | | | 3 | 397 | | | |
| | | | 4 | 259 | | | |
| 6 | 3·18 mm (0·125 in.) | i(*e*) | 1 | 591 | 375 | 365 | −2·7 |
| | | | 2 | 444 | | | |
| | | | 3 | 234 | | | |
| | | | 4 | 231 | | | |
| 7 | 3·18 mm | i(*f*) | 1 | 627 | 398 | 408 | +2·5 |
| | | | 2 | 471 | | | |
| | | | 3 | 245 | | | |
| | | | 4 | 248 | | | |
| 8 | 3·18 mm | ii(*g*) | 1 | 624 | 393 | 425 | +7·1 |
| | | | 2 | 467 | | | |
| | | | 3 | 234 | | | |
| | | | 4 | 246 | | | |
| 9 | 3·18 mm | ii(*h*) | 1 | 624 | 394 | 419 | +6·5 |
| | | | 2 | 467 | | | |
| | | | 3 | 237 | | | |
| | | | 4 | 246 | | | |
| 10 | 3·18 mm | ii(*j*) | 1 | 631 | 397 | 368 | −7·3 |
| | | | 2 | 473 | | | |
| | | | 3 | 237 | | | |
| | | | 4 | 249 | | | |
| 11 | 4·0 mm (0·157 in.) | ii(*g*) | 1 | 662 | 422 | 463 | +9·7 |
| | | | 2 | 439 | | | |
| | | | 3 | 357 | | | |
| | | | 4 | 229 | | | |

| Test | Hole size | Configuration (see figure 7) | Tapping number | mm $H_2O$ Static pressure | mm $H_2O$ Mean of tappings $M$ | mm $H_2O$ Ring reading $R$ | Discrepancy $100\left(\frac{R-M}{M}\right)$ (%) |
|---|---|---|---|---|---|---|---|
| 12 | 4·0 mm | iii($k$) | 1 | 690 | 440 | 437 | −0·7 |
| | | | 2 | 456 | | | |
| | | | 3 | 373 | | | |
| | | | 4 | 240 | | | |
| 13 | 4·0 mm | iv($l$) | — | — | 396 | 398 | +0·5 |
| 14 | | | — | — | 246 | 244 | −0·8 |
| 15 | | | — | — | 688 | 689 | +0·1 |
| 16 | | | — | — | 242 | 240 | −0·8 |
| 17 | | | — | — | 428 | 428 | 0 |
| 18 | | | — | — | 717 | 718 | +0·1 |
| 19 | | | — | — | 250 | 250 | 0 |
| 20 | | | — | — | 265 | 266 | +0·4 |
| 21 | | | — | — | 251 | 251 | 0 |
| 22 | | | — | — | 393 | 395 | +0·5 |

TABLE 1. Test results

make a smaller contribution to the ring reading. This hypothesis was tested by reconnecting the leads to the tappings in the reverse order. The resulting discrepancies fell within the same range as before in magnitude but were of opposite sign, confirming that one tapping was not making its full contribution because of an extra resistance in the associated limb of the ring.

A further ring of the same dimensions was then constructed from new tubing and fittings, and carefully supported to prevent it from distorting under its own weight. A series of tests was conducted at low, medium and high pressure differentials; tests summarized in table 1 as tests 13–22. In no test did the discrepancy exceed a 2 mm $H_2O$ differential, and the mean discrepancy over the set was +0·3 mm with a root-mean-square deviation of 1·3 mm. The standard error of the mean was 0·43.

Thus it may be concluded that the Triple-T ring gives a true average reading and that the predictions of the theory are confirmed.

## 7. Discussion

It is clear from the theory, supported by test results, that the normal form of piezometer ring is unsuitable for use in asymmetrical flow where a mean pressure measurement is required. It is also unsuitable as a consistent reference, for the pattern of the asymmetry will normally vary with the flow rate. Even under the best circumstances, where the hole is extremely small, the 'mean' is approximate, and the small size may have attendant disadvantages. In the particular case of a pipe or equipment of large diameter with relatively large tapping holes, a closely fitting normal ring should be avoided even if the flow is believed to be symmetrical and well behaved. Since the ideal Triple-T configuration gives a true mean in all circumstances, it is recommended that this form be used in all tests.

An important point, which emerged from the experimental work, is the need to construct the ring carefully to achieve this ideal. The tubing of the ring and leads generally contributes very little to the resistances, which come mainly from the holes, T-pieces and other fittings. Slight variations in the lengths of nominally identical pieces of tubing are most unlikely to have a significant influence on the results. However it is wise to construct any form of ring accurately, aiming for good symmetry and ensuring that tubing and fittings are not distorted at connexions.

## 8. Conclusions

A mathematical model of the conventional piezometer ring has been developed which shows good agreement with test results and demonstrates that this form of ring is unreliable in asymmetric flow. An alternative form of ring was shown to give a true mean pressure reading, provided care is taken in its construction, and is recommended for general use.

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