The Effect of Disturbed Flow Conditions on the Discharge Coefficient of Orifice Plates

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SUMMARY

The accurate measurement of flow rate using orifice plates depends upon many factors. One such factor is the condition of the flow in the pipe just upstream of the metering station. The values of discharge coefficient presented in the flow measurement standards are based upon axi-symmetric, fully developed turbulent velocity profiles, with no swirl component. In practice, such ideal flow conditions are very difficult to achieve, because of the effect of various pipe fittings such as bends, tees, and valves upstream of the meter. These fittings distort the velocity profile, and generate secondary flows which are only damped out very slowly by the action of turbulent shear stresses.

The aim of this paper is briefly to review the way in which a range of pipe fittings disturb the condition of flow, and then to discuss the ways in which the various classifications of disturbance affect the flow through the orifice plate. From this basic understanding of the physics of the flow field, it is possible to build up a picture of the way in which the discharge coefficient of an orifice plate will be affected in a non-ideal installation, and to appreciate the effect of such variables as the area ratio of the device.

The qualitative description given in the paper will be supported and supplemented by reference to an extensive experimental programme being carried out at BHRA Fluid Engineering in conjunction with the National Engineering Laboratory of the Department of Industry, under a Metrology and Standards Requirements Board Contract.

NOTATION

C_D discharge coefficient of orifice plate
d orifice diameter
D pipe diameter
I pressure index
m area ratio of orifice plate = $(d/D)^2$
R radius ratio of bend centre line.

1 INTRODUCTION

The accurate measurement of fluid flow rate is a problem of great importance to many industries. Although the orifice plate is one of the oldest devices for measuring pipe flows, it is still very widely used, particularly in gas-flow applications. The advantages of the orifice plate are its simplicity and low cost, and the fact that if certain rigorous installation requirements are adhered to, then the flow rate can be measured to within a fairly small tolerance, without the need for prior calibration. This paper addresses one of the problems posed by the rigorous installation conditions mentioned previously. The orifice plate discharge coefficients tabulated in the flow measurement standards (e.g. (**1**)) are based upon so-called ideal conditions. Such ideal conditions are developed at the end of long straight runs of smooth pipe, such that the fully developed turbulent velocity profile is attained in the absence of any secondary flow component. In the industrial situation, very long runs of straight pipe are probably the exception rather than the rule, and thus it is important to understand the manner, and the extent to which a disturbed flow condition will affect the accuracy of the flow rate measurement. These disturbances to the flow condition occur due to the effect of pipe-fittings such as bends, valves, tees, or reducers installed in the upstream pipework. The aim of this paper is to try and describe the way in which these typical pipe components disturb the flow. The manner in which these disturbances affect the flow field through the orifice plate, and hence the pressure distributions around the plate, can then be described in a systematic way. It is hoped that this approach will lead to an increased appreciation of the complexities of installation effects, and give the practising engineer a feel for the problems he faces, and the potential metering errors he has to guard against.

The work described in this paper is based upon many years' research effort into general internal flow systems carried out at BHRA Fluid Engineering by Miller (**2**) and an extensive experimental programme on orifice plate installation effects carried out by the present author (**3**)–(**5**).

2 ORIFICE PLATES IN UNDISTURBED FLOW CONDITIONS

Before discussing the effect of flow disturbances on orifice plate performance, it is necessary to very briefly describe the reference condition on which the understanding is to be based. Figure 1 shows in diagrammatic form a fully developed turbulent velocity profile approaching an orifice plate, and illustrates the flow patterns and pressure distributions in the vicinity of the plate. The approaching velocity profile is two-dimensional with a peak to mean velocity ratio of about 1·15. The pipe wall pressure drops slowly due to friction until about 0·2D before the plate. Here the pressure rises due to the so-called impact pressure effect. The axial momentum in the annular area of pipe defined by the orifice plate has to be destroyed, hence the pressure rise, and this portion of the flow is deflected radially inward. As the flow contracts, the pressure falls; the flow continues to contract to a point about 0·5D downstream of the meter. As the flow re-expands, there is intensive turbulent mixing, resulting in an irrecoverable energy loss, and an outlet velocity profile flatter than the

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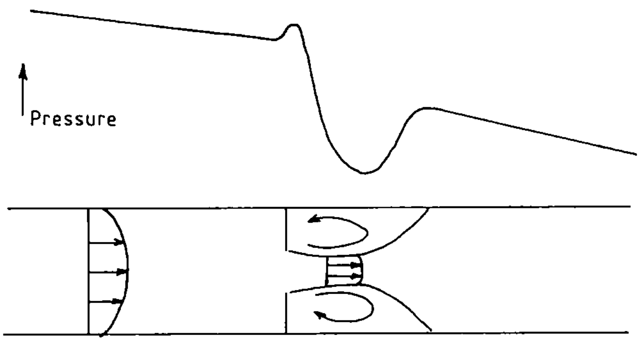

Fig. 1. Flow patterns and pressure distributions in undisturbed flow

normal, approaching profile, and with a higher turbulence level.

The effect of flow disturbances can be largely understood in terms of the effects of the velocity profile and secondary flows on the impact pressure and the jet contraction. These effects are quantified in terms of the resultant change in the discharge coefficient of the orifice, where this change is defined in percentage terms thus:

$$\text{Change in } C_D = \frac{(C_D \text{ in disturbed flow} - C_D \text{ in undisturbed flow}) \times 100{\cdot}0}{C_D \text{ in undisturbed flow}}$$

Based upon this definition, a positive change in discharge coefficient means that the use of the undisturbed coefficient (i.e. the value defined in the flow measurement standards) will result in an underestimate of the true mass flow in the pipe. One of the major problems when trying to interrelate results of different workers in the field is the precise definition of the geometry of the system tested. One of the most critical parameters in determining the shift in discharge coefficient in disturbed flows is the number, position, and orientation of the pressure tappings. In this paper, the results apply only to four circumferential tappings connected in the form of a Triple-T piezometer ring (**6**), with the tappings oriented at 45° to the plane of the immediately preceding flow disturbance.

3 FLOW DISTURBING PIPE ELEMENTS

This section concentrates on giving a qualitative description of the flow field through certain typical piping components. The components selected are typical of the whole range of pipe-fittings in terms of the sort of flow disturbance which they produce. Having thus classified 'typical' flow disturbances, these general categories will then be reviewed with respect to the effects they will produce on the orifice flow behaviour. The components selected for detailed discussion are an isolated bend, and a bend combination in more than one plane. In this paper, only a very brief description of the complex three-dimensional fluid dynamics of flow through these piping components can be given. For those who wish to pursue the subject further, Miller's book (**2**) contains a much more exhaustive account. The physical explanation of the change in discharge coefficient in disturbed flow conditions, as given below, is based on the interpretation of the experimental results in the light of the measured changes in flow quality caused by the fittings concerned.

3.1 The Effect of Isolated Bends

A bend is probably the most common of all pipe-fittings and hence its importance in this study. The distortion of the flow profile arises out of the interaction between the centrifugal and pressure forces acting through the bend. In order to balance the centrifugal forces in the flow, the pressure on the outside of a bend is higher than that on the inside. Because the velocity profile into the bend is non-uniform, the faster-moving fluid in the core tends to get displaced toward the outside of the bend. The momentum-deficient flow at the pipe wall sees the increased pressure on the outside of the bend and, unable to negotiate the adverse pressure gradient, flows around the walls to the inside of the bend. These two effects acting in combination set up a system of twin-celled secondary flows; the process is illustrated in diagrammatic form in Fig. 2. At the outlet from the bend, the slow-moving fluid that has collected on the inside of the bend again sees an adverse gradient as the circumferential pressures equalize. For bend-radius ratios of less than about 1·5, this can lead to flow separation from the inside of the bend. Both the separation and the secondary flows tend to even out the velocity profile by turbulent mixing and by feeding of energy into the near wall regions. As the degree of flow-separation increases, the turbulent mixing tends to destroy the system of secondary flows, and so, over the range of practical interest, the strength of the secondary flows increases with increasing bend-radius ratio. About five diameters downstream of the bend, the velocity profile is once again symmetrical, but there are important differences between the profile and the fully developed profile. In all cases, the velocity distribution is flatter than the fully developed profile; downstream of swept bends, because of the effect of the twin cells of secondary flow, the profiles tend to a double peak with a minimum at, or near, the centreline; with mitre bends, the intense mixing as the flow re-expands virtually destroys the secondary flows, and so the profile tends to just a single peak near to the pipe centre-line.

The distorted velocity profile, described above, decays back into the fully developed profile due to the action of turbulent shear stresses. This process is very slow because the secondary flows help to perpetuate the distortion by continually feeding energy into the pipe wall regions. The flow-measurement standards attempt to allow for this problem by specifying minimum lengths of straight pipe between the meter and the preceding fitting. This installation requirement is a function of the area ratio of the device and, for an isolated bend, ranges from about 14 diameters for an area ratio of 0·25, to 30*D*

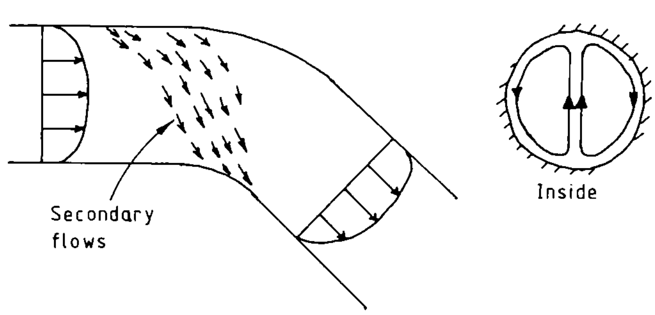

Fig. 2. Secondary flows through a bend

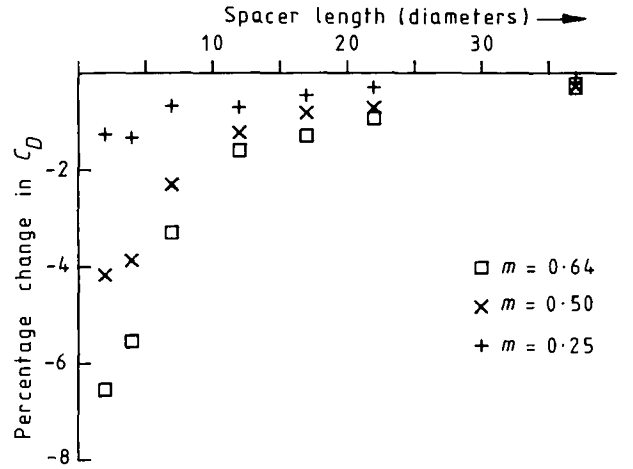

Fig. 3. Effect of an R/D = 1·5, 90° swept bend on orifice plates with corner taps

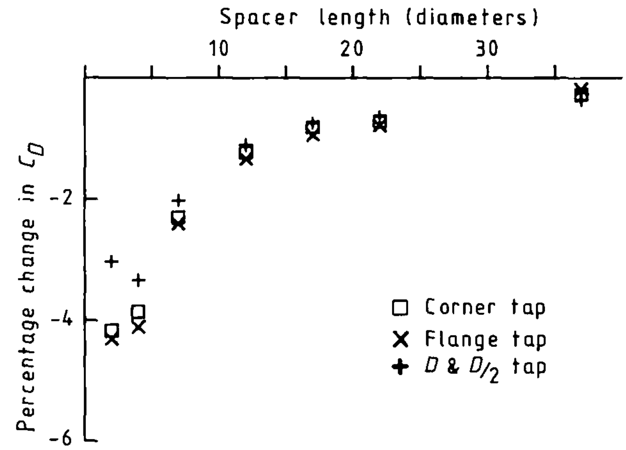

Fig. 4. Effect of tap location for an m = 0·5 orifice downstream of a 90° R/D = 1·5 swept bend

for an area ratio of 0·5 and up to 46 diameters for an area ratio of 0·64. The measured changes in discharge coefficient for these three area ratios of orifice plate, fitted with corner taps installed downstream of an R/D = 1·5 bend are shown in Fig. 3. (A detailed discussion of the experimental technique, and the reliability of results is given in (3).) The various trends apparent from the graph can be understood in terms of a comparison of the differences in the approach velocity distribution described above, and the fully developed profile.

The first point to note from Fig. 3 is that, in all cases, the change in discharge coefficient is negative (i.e. the discharge coefficient is reduced), and that the larger the area ratio of the device, the greater is the effect. The discharge coefficient of an orifice plate is a composite term, correcting for several effects which are ignored in deriving the flow-rate equation from the application of the Bernoulli equation and the law of continuity to the orifice flow. However, the dominant term in the formulation of the discharge coefficient is the contraction coefficient—the ratio of the minimum jet area to the orifice area.

It is the contraction coefficient which is mainly affected by the disturbed flow. The velocity profile downstream of a bend is flatter than the fully developed profile and so, for purposes of illustration, the comparison will be made between the fully developed profile and the extreme case of the one-dimensional profile. The one-dimensional velocity profile has a significantly higher momentum flux in the near wall region than has the fully developed profile. This higher axial momentum has to be counteracted by the orifice plate, and converted into a radial inflow of momentum. This process will clearly result in two effects; firstly the pressure rise at the upstream face of the plate will be increased, and secondly, the jet will contract further, giving a higher jet velocity and a lower downstream pressure. Since the orifice plate pressure tappings are connected across these two regions of the pressure field, it is clear that, for the same mass flow, the pressure difference for a one-dimensional profile will be greater than that for a fully developed profile (or in terms of discharge coefficient, the coefficient will be lower for the one-dimensional case).

With these concepts in mind the effect of pressure tapping location can be understood. Analysis of the pressures in the vicinity of the orifice indicates that corner, flange, and $D/2$ downstream taps are all affected to the same degree, but that there is a variation in the effect on the upstream taps. The pressure rise at the plate only extends for a fraction of a pipe diameter in the upstream direction. Consequently, the corner and probably the flange tap (depending on pipe diameter) will see the full effect of the impact pressure, whereas the tapping D upstream will not. Consequently, for the same mass flow, the corner and flange tap will see a proportionately greater increase in pressure differential than will the D and $D/2$ taps. This means that the change in discharge coefficient for a given orifice plate and a given flat profile will be less for the D and $D/2$ taps than for the corner or flange taps. This conclusion is supported by the measurements described (3), and is typically illustrated in Fig. 4 for the $m = 0{\cdot}5$ area ratio orifice downstream of an R/D = 1·5 swept bend.

A more detailed comparison of the interaction of the two profiles with the orifice plate also reveals why the larger area ratios are affected to a greater degree than the smaller. Figure 5 shows the two profiles interacting with a small and a large orifice. The greater contraction of the jet is caused by the increased momentum flux in the annular region of the pipe defined by the orifice plate. With the smaller area ratio of plate, the effect of the velocity profile on this momentum flux is, to a degree, self-cancelling; the extra momentum flux at the walls is partly compensated by the lower flux in the inner portion of the annular area. This compensating effect is not apparent for the larger area ratios where the plate only interacts with the steepened near wall velocity gradients.

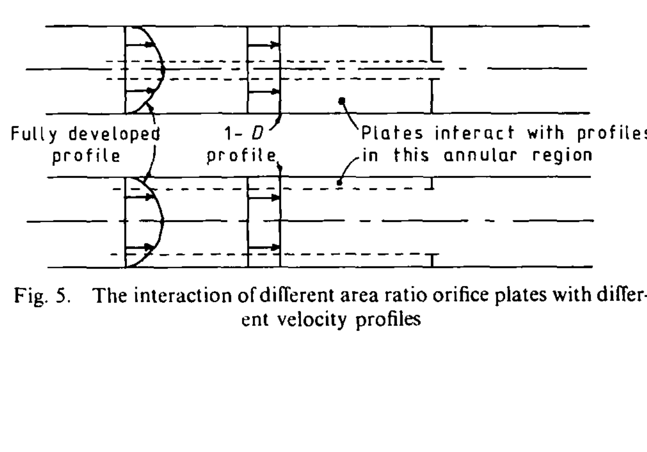

Fig. 5. The interaction of different area ratio orifice plates with different velocity profiles

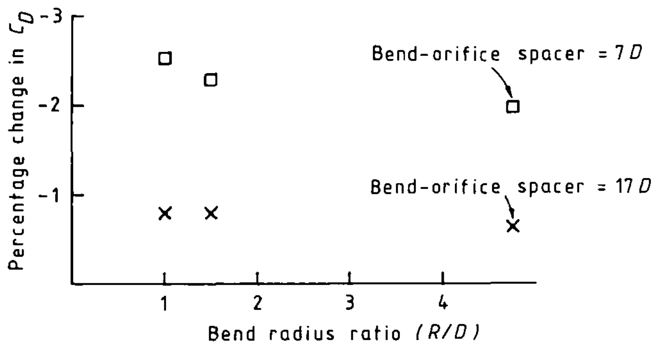

Fig. 6. Effect of bend radius ratio on an $m = 0{\cdot}5$ orifice with corner taps

The other more general point which can be made at this stage is the way in which the disturbance decays in the pipe downstream of the fitting. In the absence of any flow conditioning by flow straighteners, the fully developed profile is restored by the action of turbulent shear stresses. This is a very slow process, particularly if there are secondary flow components. This effect can be seen from Fig. 6 where the change in discharge coefficient of an $m = 0{\cdot}5$ orifice with corner taps is plotted as a function of bend-radius ratio for the meter $7D$ and $17D$ downstream of a 90° swept bend. The initial disturbance to the flow caused by the bend is greater as the radius ratio is reduced due to the flow-separation effect. However, this also reduces the strength of the secondary flows. This would imply that the change in discharge coefficient would be greater at short-fitting orifice plates for tight-radius bends, but that this disturbance would be damped out more quickly. This can be seen from Fig. 6. The other important aspect is to assess the effect of the orifice plate area ratio on the spacer length required to damp the disturbance out. The flow metering standards state that the smaller the orifice area ratio, the shorter the length of straight pipe that must be provided to ensure that any flow disturbance has been damped out. However since the disturbance is damped out only by the action of shear stresses, the area ratio of the plate cannot affect the flow in the spacer length unless there is direct interaction of the pressure distribution between the fitting and the orifice. This interaction can be seen for spacer lengths of less than about $2D$ (e.g. see Fig. 3 where the change in discharge coefficient curve changes slope at very short spacer lengths). However, for the cases of practical importance there is no such direct interaction, and the orifice plate has no effect on the flow conditions in the spacer pipe. Consequently it should be expected that the necessary length to restore fully developed flow and bring the change in discharge coefficient back to zero should be independent of area ratio. This conclusion is supported by the trends of Fig. 3 and the other similar results for other fittings given in references (3) and (4). The reason that the installation requirements in the standards are a function of area ratio is because the smaller area ratio is less sensitive to a flow disturbance. Thus, as the area ratio is reduced, it becomes increasingly difficult to discriminate between the effect of the fully developed profile and one that is a fairly close approximation to it. Despite this, the present results show that significant changes in discharge coefficient are still apparent at the spacer lengths required by the standards, particularly for the small orifice plate.

3.2 The Effect of Bends in Combination

In many situations a pipe-fitting cannot be considered in isolation, but the flow into a component—and hence the flow out—can be affected by another component upstream. These combinations of components are clearly infinite in number, since the variables include the individual component types, as well as relative orientation and spatial separation. However, one particularly important class of this type of fitting is two bends coupled in series. The most important parameter in terms of the generalized classification of disturbances is the relative orientation, and the notation used in this section is shown in Fig. 7. Once again the important aspects of the flow leaving the second bend arise out of a consideration of the two-dimensional feature of the inlet velocity profile, and the subsequently generated system of secondary flows. Once again, secondary flows are set up in the first bend due to the interaction of the pressure and centrifugal forces, but the relative orientation of the second bend dictates whether this secondary flow will be amplified or attenuated. If the bend is in the form of a 180° **U** bend, then the secondary flows set up by the first bend are almost completely counteracted by the second bend, and so the secondary flows are very weak. In the 0° **S** bend, the second bend reinforces the effect of the first bend, and a strong twin-celled system of secondary flows is established. In this sense, the classification of the disturbance type for **U** and **S** bends is the same as that for an isolated bend, and the same general arguments can be applied, since the predominant flow disturbance is in the form of a distortion of the velocity profile.

The most interesting bend arrangement, as far as this part of the discussion is concerned, is that class of combination where the two bends lie in different planes. In this particular case, all the slow-moving fluid that has collected at the inside of the first bend responds to the bend pressure distributions and takes the same route to the inside of the second bend. This process leads to one of the cells of secondary flow becoming dominant, and results in a strong bulk swirl in the outlet pipe. The intensity of the swirl is a function of the turning angle, and peaks at around 60° to 90°. This single-celled bulk swirl type of disturbance also has an effect on the axial-velocity profile, since by feeding energy across the pipe

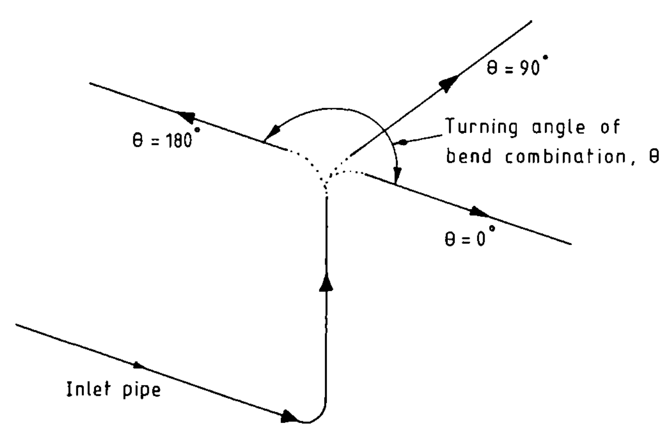

Fig. 7. Definition sketch for compound bend

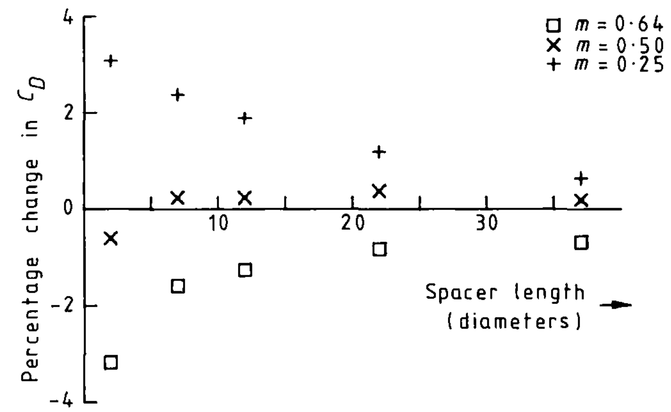

Fig. 8. Effect of 90° combined bend, $R/D = 1{\cdot}5$ on orifice plates with corner taps

section, the profile again tends towards the one-dimensional. This type of disturbance is of great importance with respect to orifice plate installations, since it has a very different effect on orifice plate behaviour than that due to distortion of velocity profile. Additionally, this class of bulk swirling flow disturbance is very persistent, and can extend for upwards of 100*D*. This fact is reflected in the installation requirements in the flow metering standards which specify lengths of up to 40*D*, 63*D*, and 82*D* for area ratios of 0·25, 0·5, and 0·64. The measured effect of two $R/D = 1{\cdot}5$, 90° swept bends in the 90° offset combination arrangement can be seen in Fig. 8. Some very clear differences between the class of flow disturbance and that discussed in the previous section are apparent from a comparison of Figs. 3 and 8. The first obvious point is that at the smaller area ratios of the device, the discharge coefficient is actually increased above that for fully developed flow profiles.

The reason for the increase in discharge coefficient in swirling flow can again be understood in terms of the interaction of the approaching flow condition with the orifice plate and the subsequent jet contraction. As has been described earlier in this section, the swirl also helps to even out the axial velocity profile, and so all the effects described in the previous section will be present, but there will be an additional influence of the swirl over and above that. The effect of this swirl can again be understood in simple terms, by momentum considerations. The approaching swirling flow has a certain tangential momentum which must be conserved as the flow passes through the plate. As the flow contracts, the rotational velocity must clearly increase, and so, as the flow re-expands, the centrifugal effects of the rotating jet result in a more rapid expansion of the jet. Thus the point of minimum jet area will move closer towards the plate, and the tendency will be for the downstream taps to record a higher pressure than would be the case for the same mass flow in the fully developed flow situation. The higher downstream pressure implies a smaller measured differential and an increased discharge coefficient, but this trend is opposed by the axial velocity profile effect, and it is the area ratio of the device which dictates which effect predominates. As discussed in section 3.1, the velocity profile effect influences the flow characteristics of a large area ratio device more than that of a small plate. However, the reverse is true in the case of the influence of bulk swirl. For a given level of swirl in the flow, the conservation of tangential momentum means that the rotational velocity is accelerated to a greater degree when passing through a smaller area ratio plate. The greater the rotational speed, the greater the centrifugal forces, and the more rapid the jet expansion will be. This effect can be seen also from Fig. 9 relative to Fig. 8. Figure 9 shows the results for a similar bend layout, except that the radius ratio of the individual bends is 0·5 (mitre) rather than 1·5. The tightening up of the bend has increased the swirl intensity and increased the discharge coefficients of all the plate area ratios above the value for fully developed flow. This result has a very important bearing on the flow metering standards, since the standards define a smaller necessary installation length the smaller the area ratio of the device. As has been discussed previously, this does not mean that the disturbance is damped out to a degree dependent on the area ratio, but that although the disturbance decays at the same rate, the sensitivity of the plate to that disturbance is a function of the area ratio. It is clear from Figs. 8 and 9 that the data in the standards is misleading relative to the classes of fittings producing bulk swirl, since at a given fitting orifice spacer length, reducing the area ratio may not reduce the error in flow measurement if the standard coefficient is used. It is also clear, from Fig. 9 in particular, that the installation requirements in the standards are inadequate for the smaller area ratios in strongly swirling flows. For the example shown in Fig. 9, the standards require, at most, 40*D* for an $m = 0{\cdot}25$ orifice, but the measured change in discharge coefficient for this combination is still at the 2·5 per cent level.

3.3 The Effect of Other Piping Components

Although only two types of piping component have been discussed in any detail, the flow disturbances produced by these fittings is typical of many. Piping components can be very broadly divided into those that produce asymmetry, and those that produce swirl. Swirling type flow is generally produced by those fittings that cause the flow direction to change in different planes in rapid succession. Such an effect can be produced by fittings other than combinations of bends—for example, a bend and a gate valve with its stem out of the plane of the bend. Fittings that only produce flow direction changes in a single plane basically produce an asymmetry-type disturbance. This asymmetry usually disappears within about 5*D* of the component, and the profile is then symmetrical, but generally flatter than the fully

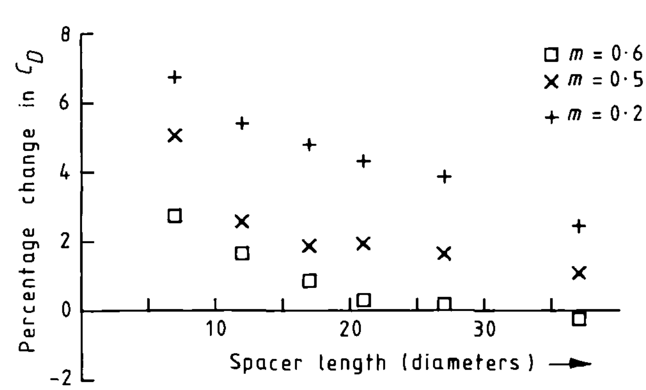

Fig. 9. Effect of 90° combined mitre bend on orifice plates with corner taps

developed profile. In many of the asymmetry-type disturbances there is a system of secondary flows as described in section 3.1; the main effect of these twin-celled rotations is to help maintain the flatness of the axial velocity profile in the outlet pipe, but they do not interact directly with the plate. Thus it is that components that produce no secondary flow (e.g. reducers, valves, etc.) affect the orifice plate in a similar way to an isolated bend. The exception to the last statement is that experimental work suggests that there may well be some Reynolds number dependence in the way a system of secondary flows interacts with the orifice plate characteristics. This hypothesis has been discussed in a previous paper (7) and further experimental work is in hand.

4 THE QUANTIFICATION OF THE EFFECT OF GENERALIZED FLOW DISTURBANCES

In the previous section, the two generalized types of flow disturbance, and their effect on orifice plate metering were discussed in qualitative terms. Clearly the major point of interest is to try and quantify the effect these disturbances may have on a given orifice plate. As part of the present investigation, an attempt has been made to develop a generalized method of predicting the changes in discharge coefficient of an orifice plate in disturbed flow. Attempts have been made in the past to relate the change in discharge coefficient to some form of kinetic energy factor or momentum coefficient of the approaching flow (**8**). The disadvantage with this approach is the need to get into the pipe and make detailed velocity traverses; in the industrial situation this is clearly impractical, if not impossible. The approach described in this paper is to use a pressure index to correlate the changes in discharge coefficient. As has been described in section 3, the effect of a disturbed flow condition is to modify the characteristics of the axial pressure distribution in the region of the orifice plate. A parameter is sought which will characterize this pressure profile, and thus the flow characteristics of the orifice plate.

During this study, several pressure indices were calculated and tested, the best one being a combination of the D and $D/2$ taps and the flange taps. The D upstream tap is used as a reference pressure, as this is in a region of the flow unaffected by the orifice. The form of the pressure profile can then be characterized by the difference between this pressure and another pressure just upstream of the plate, and a further pressure on the downstream side. These three tapping locations thus provide an undisturbed pressure, the impact pressure, and an approximation to the minimum pressure. The exact form of the parameter is

$$I = \frac{\text{pressure at } D \text{ upstream tap} - \text{pressure at flange upstream tap}}{D \text{ and } D/2 \text{ tap differential pressure}}$$

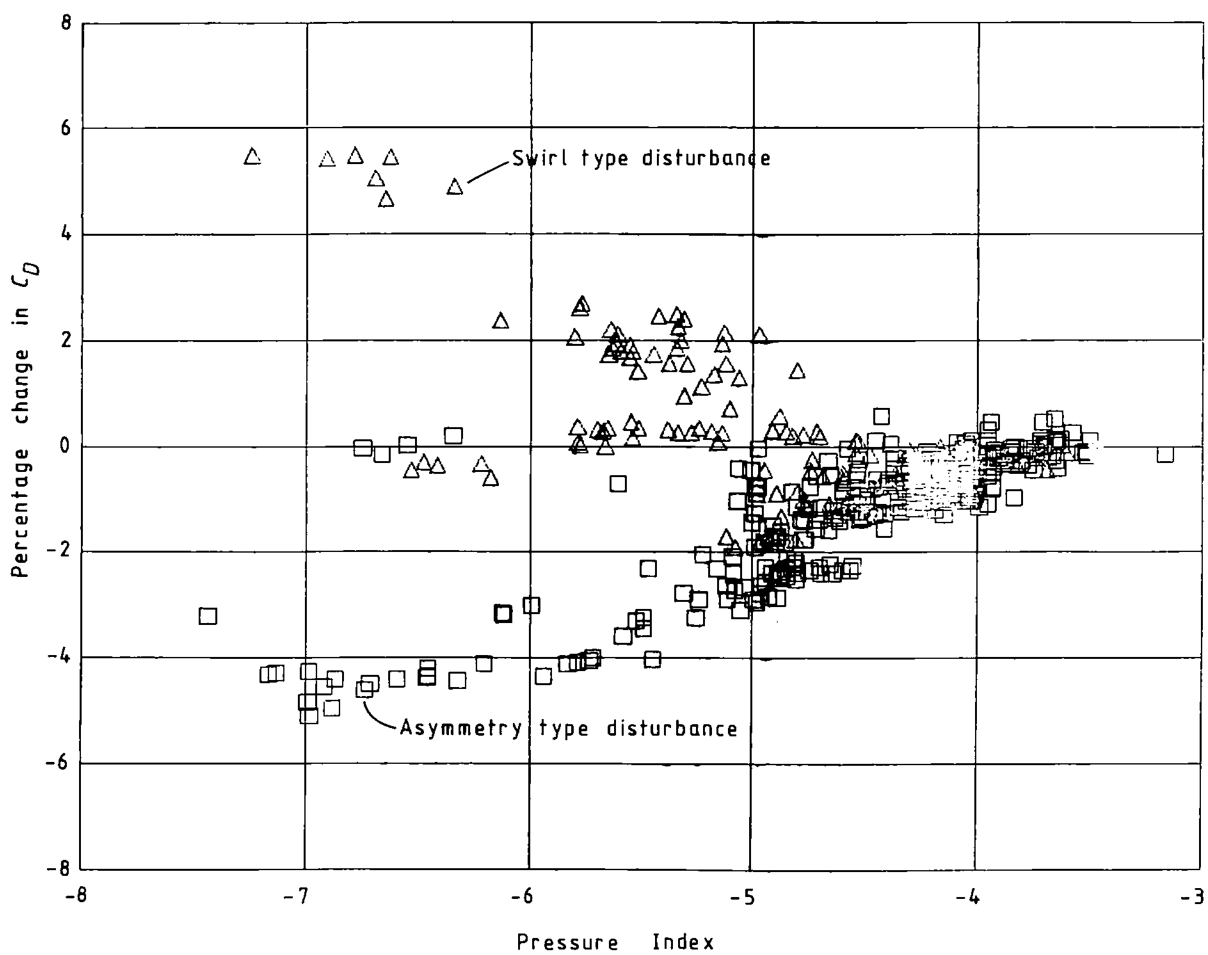

Fig. 10. Correlation of pressure index with change in discharge coefficient

Figure 10 is a plot of this parameter against the corresponding change in discharge coefficient for an $m = 0{\cdot}50$ orifice. The two shapes of point identified on the graph represent the two generalized types of flow disturbance, the squares representing asymmetry type, and the triangles, swirling type disturbances. These points represent every measurement taken during the experimental programme, and amount to something approaching 500 values. The results also represent many different fittings: bends, in isolation and in combination, of different radius ratios and turning angles, a butterfly valve and a gate valve both fully open and partially closed. Although there is a fair amount of scatter, very clear trends are apparent from which an estimate of the discharge coefficient of an orifice plate in disturbed flow could be made to within the ± 1 per cent level. The advantage of this type of parameter is that it only relies on a very limited number of static pressure measurements, and thus is potentially capable of industrial application. The problem with this parameter on the other hand is that it assumes that the only non-standard aspect of the metering installation is the approaching flow condition: that is, the meter must be ideal in all other respects, such as edge sharpness, concentricity, good tappings, etc., etc. If these conditions are not met, then applying corrections to the flow rate based on this correlation may well exacerbate the metering error. Additionally, the method also assumes a knowledge of the quality of the approaching flow so that the correct branch of the graph can be used. Perhaps the greatest use of the parameter at this stage of its development is to use it for assessing the severity of an installation effect. The measured value of the pressure index can be used to determine whether the likely change in discharge coefficient is of the order of 0·5 per cent or 5 per cent and the engineer is then in a position to assess the need for modifications to his piping layout or metering arrangement.

5 CONCLUSIONS

The piping geometry upstream of an orifice plate is very important in determining the accuracy of flow measurement. The possible configurations of the approach pipework are infinite and so this paper has tried to break these infinite number of possibilities into two general categories. This classification is based upon the form of the generalized flow disturbance. The effects of these generalized flow disturbances on the flow characteristics through the orifice plate have been discussed in qualitative terms, and illustrated by experimental measurement. A method has also been presented which attempts to quantify these effects in terms of the change in the orifice plate discharge coefficient.

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