Effects of upstream bends and valves on orifice plate pressure distributions and discharge coefficients

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An extensive series of tests has been carried out to determine the effect of upstream fittings (bends, valves, bend–bend and bend–valve combinations) on the discharge coefficients of orifice plates. The pressure data acquired during these tests have been studied in detail and a number of general recommendations for reducing the errors associated with using orifice plates in disturbed flow conditions are presented in this paper. It is noteworthy that other tapping combinations in place of the standard *D* and *D*/2, flange and corner combinations were less sensitive to disturbances in the flow so that their use could result in smaller errors. Of more direct practical use, as the internationally standardized tapping arrangements are unlikely to be changed, it was established that the use of a further pressure measurement would allow the change in the discharge coefficient for corner and flange taps to be estimated with reasonable accuracy for most adverse flow conditions

Key words: *orifice plates, flow discharge coefficient, flow measurement*

The International Standard for the use of orifice plates to measure flowrates[1] in pipelines specifies certain minimum lengths of straight pipe between any upstream fittings, such as bends or valves, and the orifice plate. These minimum lengths are 5–80 pipe diameters, depending on the nature of the upstream fittings and the diameter ratio of the orifice plate. In many industrial situations it is impracticable to provide such upstream lengths to ensure that the effect of the upstream fittings can be ignored: in these circumstances, it is important to establish what additional uncertainty should be attached to the measurements. Also, if the change in the discharge coefficient can be predicted with reasonable accuracy, then the orifice plate can be used with a corrected discharge coefficient, resulting in only a relatively small increase in the uncertainty of the measurement.

While a significant amount of information on the effects of upstream fittings on orifice plate performance has been published (for example, by Clark[2], Schröder[3], Alleon[4] and Nagel and Jaumotte[5]), there are numerous areas in which no information has been available. To remedy this situation, an extensive series of tests was carried out by staff at the British Hydromechanics Research Association (BHRA), under the guidance of NEL, as part of the research programme undertaken by the Flow Measurement Division for the Department of Industry's Metrology and Standards Requirements Board. The primary results have been presented in a series of reports issued by the British Hydromechanics Research Association[6–11]. These reports include a literature survey, a comparison of the results obtained with those of other workers, and a discussion of the nature of the disturbed flow produced by the various fittings and its effect on the discharge coefficient. Irving[12] published a general description of the programme and of the results for single components and for two bends.

This paper describes the results of a detailed study of the effects of the disturbances on the pressure distributions upstream and downstream of the orifice plate, and, following from this study, offers proposals for reducing the errors associated with using orifice plates in disturbed flow.

Summary of tests

The BHRA tests were carried out using air at close to ambient conditions in a pipe with an internal diameter of 0.203 m (8 in). Three orifice plates with area ratios, *m*, of 0.25, 0.50 and 0.64, respectively, were tested.

Tables 1 and 2 list the 37 combinations of bends and valves which were used to generate the disturbed flows; for most of these combinations, each orifice plate was tested at several positions downstream of the fittings. For each configuration, pressure readings were usually recorded for five different flowrates. Differential pressures were automatically recorded across corner, flange and *D* and *D*/2 tappings; gauge pressure was recorded at the three

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upstream tappings and at a $D/2$ upstream position. At each of these seven axial positions, four tappings were distributed radially at 45° to the horizontal and vertical pipe diameters; in total, 28 pressure measurements were recorded for each test.

The orifice plates were tested over the following ranges of Reynolds numbers, based on conditions at the orifice:

$m = 0.64 \quad 5\times10^5 < Re < 8\times10^5$

$m = 0.50 \quad 4.4\times10^5 < Re < 6.9\times10^5$

$m = 0.25 \quad 3.6\times10^5 < Re < 4.5\times10^5$.

Table 1 Single component and bend–bend configurations tested

Description	Number of diameters of straight pipe: Between fittings	Upstream of orifice plate
Single component:		
1 Bend, *R/D* = 1.5		2, 4, 7, 12, 17, 22, 37, 67
2 Bend, *R/D* = 1.0		2, 7, 22
3 Bend, *R/D* = 4.75		2, 7, 17
4 Mitre bend		2, 7, 12
5 30° swept bend, *R/D* = 1.5		2, 7, 17
6 60° swept bend, *R/D* = 1.5		2, 7, 17
7 Butterfly valve, fully open		4, 7, 17
8 Butterfly valve, disc angle 51°		4, 7, 17
9 Gate valve, fully open		2, 7, 17, 37
10 Gate valve, one-third closed		2, 7, 17, 37
Two bends:		
11 *R/D* = 1.5, 90 offset	0	2, 7, 12, 22, 37
12 *R/D* = 1.5, 90 offset	5	7, 11, 21
13 *R/D* = 1.5, 90 offset	11	7, 11, 21
14 Mitre, 90 offset	0	7, 12, 17, 21, 22, 27, 37
15 *R/D* = 4.75, 90 offset	0	7, 14, 22
16 *R/D* = 1.5, U-configuration	0	7, 17, 27
17 *R/D* = 1.5, U-configuration	5	7, 17, 27
18 *R/D* = 1.5, S-configuration	5	7, 17, 22
19 Mitre, U-configuration	0	7
20 *R/D* = 1.5, S-configuration	0	7, 12

The undisturbed pressure distribution

To identify the effects of the upstream disturbances on the pressure distribution close to the orifice plate, it is necessary to know the undisturbed pressure distribution.

Stolz[13], in deriving a universal equation for orifice plate coefficients in undisturbed flow, found that experimental data for the variation of pressure upstream of an orifice plate could be adequately represented as a linear decrease from the plate to a position 0.4333*D* (where *D* is the pipe diameter) upstream of the plate: upstream of this position the pressure could be regarded as constant.

Taking *P* to be the pressure relative to this constant upstream pressure, expressed as a percentage of corner differential, the correlation is:

$$P = \left(1 - \frac{l}{0.4333D}\right) \times 0.13\left(\frac{m^2}{1-m^2}\right) \quad \text{for } l < 0.4333D$$

$$P = 0 \quad \text{for } l \geq 0.4333D$$

where l is the distance upstream of the plate. The correlation was valid for values of the area ratio, m, up to at least 0.56.

Table 3 shows the values of P at the upstream flange and corner tappings obtained from the BHRA calibration tests and also those derived using the Stolz correlation.

The experimental data used by Stolz in deriving the correlation showed a scatter about the correlation line of ≥1% of corner differential pressure. This scatter is probably largely due to variations in the velocity profile upstream of the orifice plate, caused mainly by differences in the roughness of the pipe wall relative to the diameter. For a relatively smooth pipe, the velocity profile is flatter[14] and, thus, because more of the velocity is distributed near to the pipe wall, the increase in upstream pressure will be greater. This explanation is supported by the fact that the experimental data which are above the Stolz correlation line tend to be associated with the larger pipe sizes, which will in general be relatively smoother. The differences between the BHRA data and the Stolz correlation can thus be explained by the relative smoothness of the 203 mm plastic pipe used.

Notation

E_{CC}	Percentage change in corner tap discharge coefficient
E_{DD}	Percentage change in D and $D/2$ tap discharge coefficient
E_{FF}	Percentage change in flange tap discharge coefficient
D	Internal diameter of pipe
I_C	Corner tap pressure index
I_F	Flange tap pressure index
I_{CO}	Value of I_C in undisturbed flow
I_{FO}	Value of I_F in undisturbed flow
m	Orifice plate area ratio
P	Pressure relative to that at upstream D tap, expressed as a percentage of undisturbed corner differential pressure
P_{DC}	Gauge pressure at downstream corner tap
P_{DF}	Gauge pressure at downstream flange tap
P_{UC}	Gauge pressure at upstream corner tap
P_{UD}	Gauge pressure at upstream D tap
P_{UF}	Gauge pressure at upstream flange tap
R	Radius of pipe bend

Results of analysis of pressure distributions

The full results of the analysis are given elsewhere[15]. It is only practicable to indicate the trends of the results in this paper and, therefore, pressure deviations for three fitting arrangements are shown in Fig 1 for each of the three orifice plates. The measured pressure deviations, expressed as a percentage of the undisturbed corner tap differential pressure, have been averaged over a number of tests representing a range of Reynolds numbers, and then averaged over the four radial tapping locations. The values at the different axial tapping positions have been joined by straight dashed lines; the length of the dashes is related to the length of straight pipe between the fittings and the orifice plate, so that the effects of increasing this length in decreasing the pressure deviations can be seen in the diagrams.

The first column of diagrams in Fig 1 shows the effect of a single bend upstream of an orifice plate: the upstream pressure is increased, and the downstream pressure is decreased; the magnitude of both effects increases markedly with increase in the area ratio. This pattern is typical of that which occurs in disturbed, non-swirling flows.

When a second bend in a different plane (offset by 90°) is introduced five pipe diameters upstream of the original bend, some swirl occurs in the flow at the orifice plate. The effect of this can be seen in the second column of diagrams in Fig 1. The deviations upstream and downstream are reduced significantly in magnitude for the two larger area ratio plates; for the small ($m = 0.25$) area ratio plate, the deviations are negligible.

When the two offset bends are installed adjacent to each other, the resultant strong swirl causes positive pressure deviations downstream. The third column of Fig 1 shows a large increase for the $m = 0.25$ plate, leading to an increase in discharge coefficient: for the $m = 0.50$ plate the positive downstream deviations almost mirror the upstream deviations, so the changes in the discharge coefficient are negligible. For the $m = 0.64$ plate, the downstream increase does not compensate for the positive upstream deviations, and the discharge coefficients are decreased.

A general assessment of the overall analysis showed that:

(1) The magnitude of the deviations tends to increase markedly with increase in area ratio.

(2) Almost without exception, the upstream deviations are positive and increasing as the plate is approached.

(3) Fitting combinations which create swirl, such as two adjacent bends offset by 90°, or a gate valve with upright valve stem combined with a horizontal bend, cause positive downstream deviations, especially for the $m = 0.25$ plate.

(4) The $D/2$ downstream values and, to a lesser extent, the upstream corner values, appear more variable than those at other positions. (Stolz[13] shows that even in undisturbed flows the experimental data in the vicinity of the $D/2$ downstream tapping is relatively unreliable.)

Table 2 Bend–valve and valve–bend configurations tested

Valve* setting	Valve stem orientation	Number of diameters of straight pipe: Between fittings	Upstream of orifice plate
Bend–valve:			
21 1/3 closed	Upright	0	2, 4, 7, 22
22 2/3 closed	Upright	0	2, 7
23 1/3 closed	Inside	0	7
24 1/3 closed	Outside	0	7
25 1/3 closed	Upright	2	4
26 Fully open	Upright	5	7
27 1/3 closed	Upright	5	2, 7, 22
28 1/3 closed	Upright	9	7
29 1/3 closed	Upright	20	7
Valve–bend:			
30 1/3 closed	Upright	0	2, 4, 7, 22
31 1/3 closed	Upright	5	7, 22
32 1/3 closed	Inside	0	7, 17
33 1/3 closed	Outside	0	7
34 1/3 closed	Inside	5	7
35 1/3 closed	Outside	5	7
36 2/3 closed	Inside	5	7
37 2/3 closed	Upright	0	7

** The valve setting is measured by stem travel*

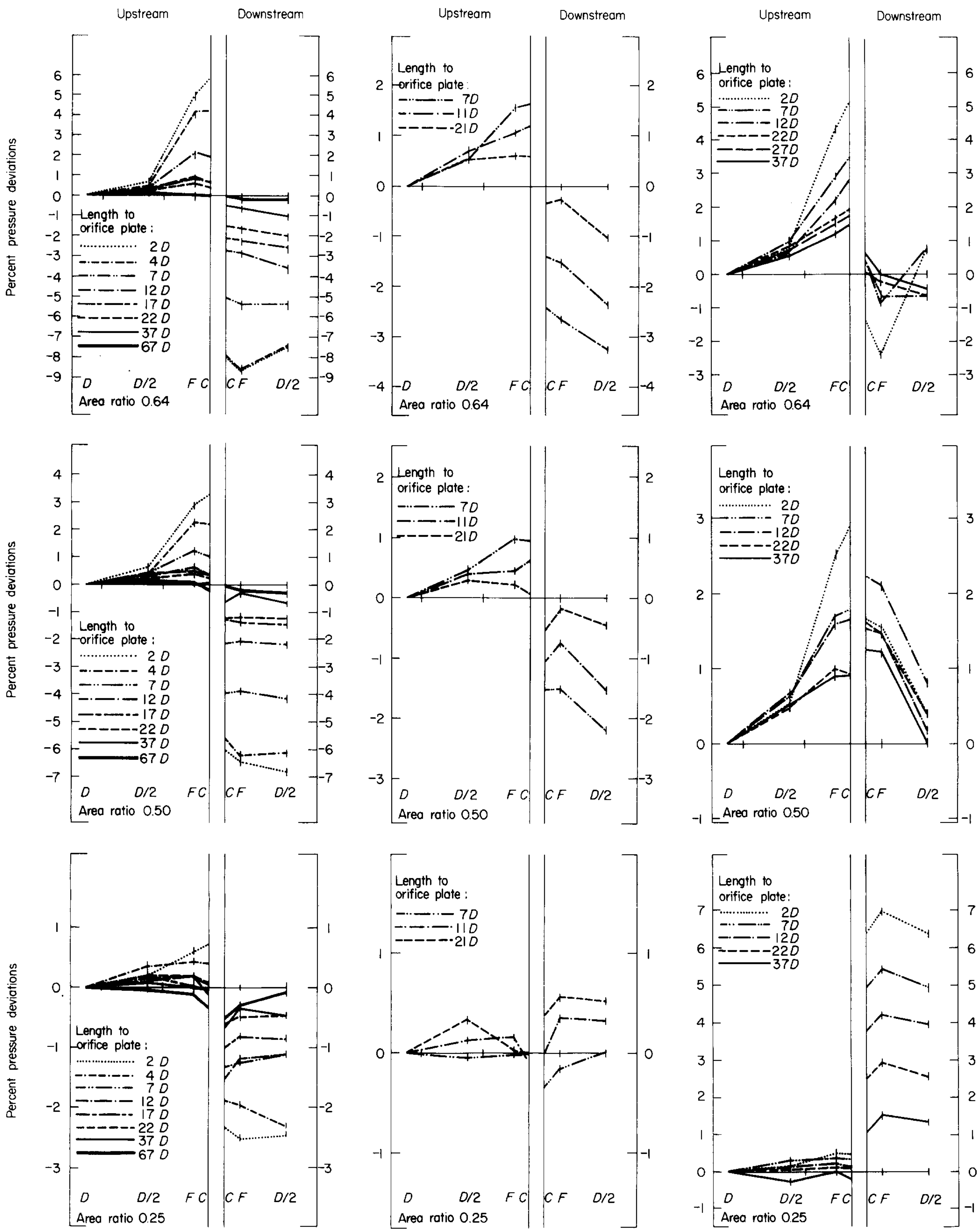
Table 3 Pressure increase upstream in undisturbed flow (Percentage of corner differential)

		m: 0.25	0.50	0.64
Flange:	BHRA	0.85	3.7	6.5
	Stolz	0.63	3.2	6.6
Corner:	BHRA	1.2	5.5	10.5
	Stolz	0.88	4.4	9.3

The reasons behind the first three of these features can be understood in qualitative terms: the BHRA reports discussed the nature of the flow created by the various disturbances and the way it reacts with the different orifice plates. For non-swirling flow, the crucial feature is the radial distribution of axial velocity: with a flat velocity profile, a greater amount of inward radial momentum is created, leading to an increase in the pressure build-up upstream of the orifice plate; on the downstream side, increased contraction of the jet issuing from the orifice leads to a decrease in the pressure. These effects add to each other, in proportions which vary according to the tappings used, to decrease the value of the discharge coefficient.

For swirling flow, the angular momentum tends to expand the size of the downstream jet, leading to higher values of downstream pressure. For small area ratios, this downstream increase in pressure is greater than the upstream increase caused by the distortion of the velocity profile; the result is a net increase in the discharge coefficient.

For the purpose of the subsequent discussion, it is convenient to divide the configurations tested into three groups, according to the degree of swirl



Single bend, R/D = 1.5

Two bends, R/D = 1.5, 90 degree offset
5D spacer between bends

Two bends, R/D = 1.5, 90 degree offset
no spacer between bends

Fig 1 Pressure deviations in three types of disturbed flow

generated. Configurations with two adjacent components which produce disturbances in different planes, such as two bends offset by 90°, or a horizontal bend combined with a partially closed gate valve with its stem vertical, generate significant swirl. In Tables 1 and 2 these configurations are numbered 11, 14, 15, 21, 22, 30 and 37; of these, 11 and 14 (two $R/D = 1.5$ bends and two mitre bends, respectively) generate strong swirl, the remainder generate moderate swirl. For the other configurations, the swirl can be ignored.

From a study of the behaviour of the pressure deviations, two approaches for minimizing the error associated with the use of orifice plates in disturbed flow have been investigated in some detail. These are: the use of tapping combinations other than the standard corner, flange or D and $D/2$ combinations, and the use of an extra upstream differential pressure measurement to obtain an estimate of the value of the error.

Alternative combinations of tappings

As noted previously, the disturbances investigated in the BHRA tests lead, in general, to an increase in the pressure build-up upstream of the plate; however, downstream deviations showed few consistent trends (if swirling flow is excluded) except that the variability at the $D/2$ tapping was greater than at the other two tappings. This suggested that a discharge coefficient based on the D upstream position and either the corner or flange downstream positions may prove more reliable in disturbed flow.

Changes in the discharge coefficients for the three standard tapping combinations, identified as C_{DD}, C_{FF} and C_{CC}, were compared, therefore, with those from two new combinations, identified as C_{DC} and C_{DF}. The percentage changes in the discharge coefficients are defined, for example, as:

$$E_{DD} = 100\left(\frac{C_{DD} \text{ in disturbed flow}}{C_{DD} \text{ in undisturbed flow}} - 1\right)$$

The percentage changes were plotted against the number of diameters of straight pipe between the fittings and the orifice plate on a logarithmic scale.

Figs 2(a) and (b) show the results for the flange and DF taps for the $m = 0.64$ area ratio orifice plate. The full detailed results for all the combinations are given elsewhere[15]; no attempt has been made in Fig 2 to differentiate between the different installation conditions.

Table 4 gives the average magnitude of the changes, excluding the configurations generating strong swirl (configuration No 22 at $2D$, which gave exceptionally large changes, is also excluded). For the $m = 0.25$ area ratio plate, the average change does not differ significantly between the different tapping types. For the $m = 0.50$ and $m = 0.64$ area ratio plates, the D and $D/2$ (DD) combination is the best of the standard tapping combinations, but the DC and DF combinations are significantly better than any of the standard combinations.

Pressure indices for correlating discharge coefficient changes

Irving[12], using the BHRA data for single fittings and for bend–bend combinations, investigated correlations between changes in discharge coefficient and

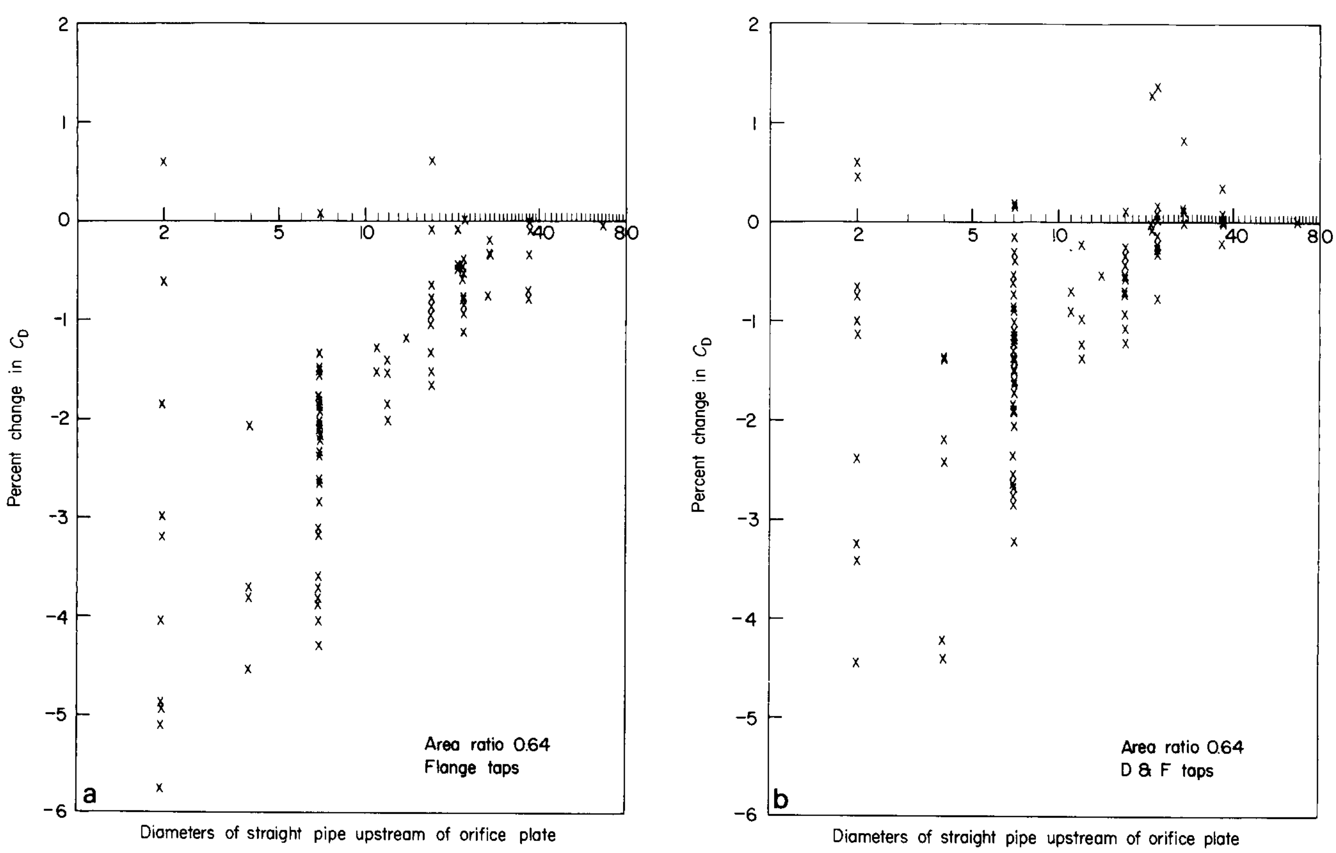


Fig 2 Discharge coefficient changes for FF and DF tapping combinations ($m = 0.64$)

various pressure indices in the form:

$(P_{UC}-P_{UD})/\Delta P$ or $(P_{UF}-P_{UD})/\Delta P$

where P_{UC}, P_{UF} and P_{UD} are the pressures at the upstream flange, corner and D positions, respectively, and ΔP is one of the three standard differential pressures. Clearly, the use of such an index requires an extra pressure measurement, but this may be acceptable if the change in the discharge coefficient can subsequently be estimated with some confidence.

This approach has now been carried further by re-examining this type of correlation in some detail, and by including the bend–valve and valve–bend data (which was not available at the time of the original investigation). The following correlations are illustrated in Figs 3 and 4:

$$E_{CC} \text{ with } I_C = \frac{P_{UC}-P_{UD}}{P_{UC}-P_{DC}} \times 100$$

$$E_{FF} \text{ with } I_F = \frac{P_{UF}-P_{UD}}{P_{UF}-P_{DF}} \times 100$$

P_{DC} and P_{DF} are the pressures at the downstream corner and flange taps respectively. Configurations generating strong or moderate swirl, and tests with only two diameters between the fittings and the orifice plate, have been excluded.

Table 4 Average of magnitude of discharge coefficient percentage changes (excluding strong swirl configurations)

m	CC	FF	DD	DC	DF
0.25	0.56	0.56	0.48	0.55	0.55
0.50	1.28	1.25	0.99	0.87	0.85
0.64	2.11	2.09	1.61	1.12	1.20

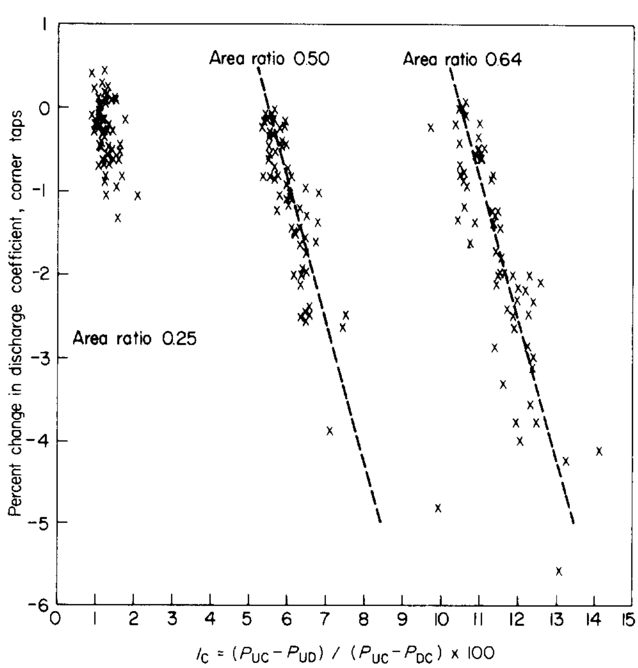


Fig 3 Corner tap discharge coefficient changes correlated with I_C

For the $m = 0.50$ and $m = 0.64$ data, correlation lines of the form:

$$E_{CC} = -1.7(I_C - I_{CO})$$

and

$$E_{FF} = -1.7(I_F - I_{FO})$$

where I_{CO} and I_{FO} the undisturbed flow values of I_C and I_F, respectively, are shown in Figs 3 and 4. For the $m = 0.50$ plate:

$$I_{CO} = 5.5$$

and

$$I_{FO} = 3.7$$

For the $m = 0.64$ plate:

$$I_{CO} = 10.5$$

and

$$I_{FO} = 6.6$$

No attempt has been made to find correlations for the $m = 0.25$ area ratio plate, as clearly such correlations would have little validity.

The following configurations showed significant deviations from the correlating functions and are not plotted:

No 19 – two adjacent mitre bends, U-configuration
No 36 – 2/3 closed gate valve (stem inside bend)–5D–bend.

For the remaining configurations, it can be seen that the correlation functions can generally be used to predict the changes in discharge coefficient to within ≈1%. Configurations giving moderate swirl tend to give smaller decreases than predicted by the correlation functions, while decreases resulting from single bends are mostly larger. It should be noted that the correlations are not valid when they predict positive changes.

Because the flange taps are defined as being 1 in (25 mm) from the orifice plate, the relative spacing of the taps, as a fraction of pipe diameter D, varies with D; for the 8 in (200 mm) pipe the relative position is $D/8$. The flange tap correlations are based only on data for an 8 in pipe: however an examination of the overall evidence[15] suggests that the correlations will be suitable for any pipe size $> \approx 6$ in (150 mm).

Values of I_{CO} and I_{FO} should be obtained from calibration. It is possible to estimate them[15], but the additional uncertainty (described previously) will reduce the usefulness of the correlations.

A correlation for D and $D/2$ taps[15] was found to be less satisfactory than the ones for corner and flange taps.

Asymmetry and orientation of pressure tappings

For each axial tapping location, as mentioned previously, pressures were recorded from four taps distributed circumferentially at 45° to the horizontal and vertical. A study of the dependence of pressure on tap orientation showed that for some configurations such as single bends, which are known to

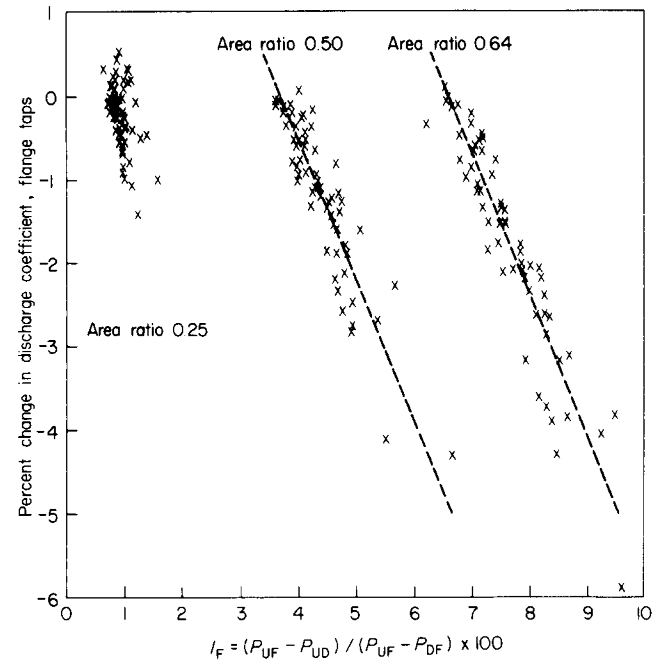


Fig 4 Flange tap discharge coefficient changes correlated with I_F

produce asymmetric velocity profiles, there was some pattern in the circumferential variation of pressure, but in general the random variations were greater. No useful general conclusions could be obtained from these data, for example, about the optimum orientation of a pressure tapping, if only one is to be used.

The results discussed previously have been based on the averages of the four pressure readings. It is recommended that a Triple-T piezometer arrangement[16] should always be used in disturbed flow to provide the most reliable average pressure readings.

Recommendations

To avoid large errors when using orifice plates in disturbed flow, the following recommendations are appropriate:

(1) Except for configurations which may be expected to generate strong swirl, use a small area ratio orifice plate whenever possible.

(2) For configurations similar to those tested, estimate the change in the discharge coefficient from the detailed information in Reference 15.

(3) Except for configurations generating strong swirl, use DC or DF tap combinations for area ratios of $\geqslant 0.5$: the discharge coefficients can be predicted from the universal equation in the International Standard[1]. Of the standard tappings, the D and $D/2$ tappings were found to be the best. (Note that for a 2 in (50 mm) pipe, DF is identical to D and $D/2$, and for a larger diameter pipe DF is almost the same as DC; the important feature is that the downstream tap should be reasonably close to the downstream face of the orifice plate, preferably within approximately $D/8$.) For small area ratios, the tapping positions are of less importance.

(4) For configurations generating strong swirl, use any of the standard tapping combinations with an area ratio of $\geqslant 0.50$.

(5) For area ratios $> \approx 0.4$, the correlations in Figs 3 and 4 can be used for non-swirling flow with standard corner or flange tappings. These require an extra upstream pressure to be measured during calibration and during use. The correlations are not suitable for flange taps in a pipe of <150 mm diameter. The changes in discharge coefficient can generally be estimated to within 1%.

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