THE NEL ORIFICE PLATE PROJECT

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SUMMARY

This paper reviews previous work to investigate the effect of upstream edge sharpness on the discharge coefficient of orifice plates. It traces the development of Standard requirements for edge sharpness and discusses the need for more guidance in the manufacture and inspection of orifice plates.

The NEL project to provide new experimental data on the effect of edge sharpness and other defects is described in detail. The main results indicate that the present criteria for edge sharpness are realistic, but the rejection of large orifice plates for very slight visible imperfections is perhaps unnecessarily stringent.

1 INTRODUCTION

An earlier version of this paper, presented at the 1986 Workshop, outlined the proposed project and gave relevant background information. The present paper records the outcome of the project and indicates the need to consider a revision of the tolerances required in some aspects of the current orifice plate standards. However, for completeness, a brief summary of the previous work, including the most recent, and the main requirements of the current standards are included in this sequel.

While the use of orifice plates to measure fluid flow is well defined in the current international Standard[1], there are some aspects of their manufacture and inspection which are not specified in sufficient detail.

One area which gives particular difficulty and, on occasions, grounds for debate is that of the edge sharpness requirement. Most people involved in the use of orifice plates are aware of the great importance of the square edge, but there is no convincing evidence to support the criteria for visual inspection given in various editions of the standards. For small pipe sizes (less than 125 mm bore) the limiting edge radius of 0.0004d is well nigh impossible to achieve and measure. For larger sizes, the edge sharpness requirement is easier to meet, but the rejection of plates showing 'any peculiarities visible to the naked eye' may be unnecessarily stringent and expensive.

Another deficiency in the current Standard is the quality of surface finish of the downstream face of an orifice plate. Again qualitative, but not quantitative, guidance is given.

The NEL orifice plate project was therefore undertaken to investigate three important topics:

a the effect of upstream edge sharpness to determine at what degree of rounding the orifice coefficient begins to change;

b the effect of local damage to the upstream edge or face of an orifice plate; and c the effect of the finish of the downstream bevel and the surface roughness of the downstream face.

An important part of this project was the survey of previous literature, covering earlier experimental work, and the evolution of the current standards. Equally important for the manufacture and testing of the orifice plates was the provision of measuring instruments of sufficiently good performance to resolve the small differences in the parameter being investigated and their effect on the orifice coefficient.

2 PREVIOUS WORK

Probably the first relevant reference to edge sharpness effects was in the early 1930s when Professor S R Beitler[2] examined microscopically the edges of plates which gave coefficients that were higher than expected. Although he considered them to be slightly rounded, it was not possible to measure the radius at that time without cutting up the plates.

It was not until the 1960s that a major experimental programme was attempted in which measurements of both edge sharpness and the discharge coefficient were made. Herning[3,4] and his colleagues carried out a programme of tests on a series of different diameter ratio orifice plates installed in meter runs of 50, 100 and later, 150 mm diameter. The edges of the orifice plates were progressively rounded with emery paper and a lead foil method was used to measure the edge radius before each successive calibration.

The results of their work were best summarised in Fig. 6 of Reference 4, which was reproduced as Fig. 1 in the 1986 NSFM Workshop paper. This showed that the effect of the edge depends only on the ratio of the radius of the edge to the orifice diameter.

More recently, Crocket and Upp[5] made further tests using 75 mm (3-in) dia. plates of 0.2, 0.4 and 0.6 dia. ratio and used the lead foil technique to determine the edge radius.

A little later Benedict[6] and his co-workers investigated the edge effect with 0.5 dia. ratio plates in a 101.6 mm (4-in) nominal bore test-line. Some of the plates were rounded to a radius of about 0.2 mm to represent an extreme case of edge roundness. Both optical and lead foil measurements were used to determine the edge radius.

All the above investigations were concerned with the effect of gross changes of the edge radius. Another series of tests were made by Spencer, Calame and Singer[7] in the 1960s on the production of orifice plates to the then current standard and the errors that could arise if care were not taken and the quality of finish required was not obtained.

Contemporary work on the effect of orifice plate condition has been carried out by Studzinski et al[8] who investigated the influence of surface roughness, solid and liquid deposits, and of nicks and burrs on the accuracy of flow measurement.

3 STANDARDS

The first international Standard on orifice plates[9] was published by the International Federation of the National Standardising Associations (ISA) in 1936. It included a graph showing the effects of 'dullness' of the edge. No qualitative description of this 'dullness' was given, but the graph is believed to have resulted from the work of Witte in the early 1930s.

Owing to the difficulty of measuring edge radius, most subsequent standards seem to have specified that the edge be sharp and left it to the user to satisfy himself that this has been achieved. Little guidance has also been given on how to machine a satisfactory sharp edge, quite a problem for some materials, especially for small orifice diameters.

In the ASME Power Test Code[10] PTC 19.5; 4-1959 it states:

> "e The inlet edge of the orifice shall be square and sharp, free from either burrs or rounding, so that when viewed without magnification a beam of light is not reflected visibly by the edge."

The German Standard DIN 1952 published in 1963 commented that a reflected ray of light from a rounding radius of 0.05 mm is just visible to the naked eye[11]. It was concluded that visual inspection could only be justified if the bore diameter were greater than 125 mm, at which value the edge radius would be 0.0004d, the criterion given for a sharp edge.

The revised British Standard BS 1042[12] published in 1964 included the same criterion for the sharp edge in the specification of the orifice plate. Clause 54 contained the following requirement:

> "d Upstream edge of orifice. The upstream edge of the orifice shall be square and free from burrs or wire edges. It may be regarded as square if its radius of curvature nowhere exceeds 0.0004d."

Elsewhere in the same standard some guidance was given on how to produce such an edge. Clause 40 included the statement:

> "A high quality of manufacture is necessary to meet the requirements detailed in Sections 7-14 especially for devices to be used in smaller sizes of pipe. The square edge of orifice plates may conveniently be produced by taking a fine cut, from the centre outwards, after the orifice has been bored; polishing or cleaning with emery cloth is not advisable. There must of course be no burrs or wire edges."

ISO 5167, 1980, which was adopted as BS 1042, 1981[13], incorporated basically the same message in clause 7.1.6.

> "7.1.6 Edges G, H and I
>
> 7.1.6.1 The upstream edge G and the downstream edges H and I shall have neither wire edges, nor burrs, nor, in general, any peculiarities visible to the naked eye.
>
> 7.1.6.2 The upstream edge G shall be sharp. It is considered so if the edge radius is not greater than 0.0004d.
>
> If $d \geq 125$ mm this condition may generally be considered as satisfied by mere visual inspection, checking that the edge does not seem to reflect a beam of light when viewed with the naked eye.
>
> If $d < 125$ mm visual inspection is not sufficient but this condition may generally be considered as satisfied when the upstream face of the orifice plate is finished by a very fine radial cut from the centre outwards.

> However, if there is any doubt as to whether this condition is satisfied, the edge radius must be actually measured."

No guidance is given in the standard on how the edge radius should be measured, but a Code of Practice for ISO 5167 is being prepared and this will include brief notes on three suitable techniques, viz lead foil, casting and stylus methods.

4 NEL EQUIPMENT

4.1 Calibration Line

As all known previous work at the time of starting the project was limited to pipes of diameters of 150 mm or less, the present work was based on 300 mm (12-in) nominal bore pipe as being more representative of the sizes currently used in gas transmission. Accordingly, the calibration line shown in Fig. 1 was set up. Flow through the line was induced by a large centrifugal fan capable of developing a pressure difference of 9-13 kPa (36-53 inches water) over the range of flowrates required.

To facilitate repeated removal and replacement of the test orifice plates a metering tube incorporating a junior orifice fitting was chosen and this was provided with two pairs of flange tappings 180° apart. The upstream length of pipe was designed to satisfy ISO 5167, Table 3, for an expander 0.5D to D over a length of 1-2D, which for an 0.75 dia. ratio orifice plate (the largest likely to be used) was 38D. With the pipe sections that were available, 39D was in fact the length used.

In order to maintain sufficiently high Reynolds numbers to obtain near constant values of discharge coefficient over a small range of flowrate with the limited pressure difference developed by the fan, it was necessary to minimise the resistance caused by the reference flowmeter. Therefore, instead of using a second orifice plate for this, a set of three venturi nozzles for operation in free inlet condition were designed. Each nozzle was sized to correspond to one of the three orifice plate diameter ratios in order to give comparable ranges of differential pressure. The optimum size was rounded to the nearest standard pipe size to facilitate mounting on the diffuser section. Thus nominal bores of 100, 150 and 200 mm were aimed at. The nozzles were manufactured in GRP (glass reinforced plastic) and calibrated against secondary standard orifice plates.

4.2 Instrumentation

Differential pressures of the inlet flowmeter and the test orifice plate were measured using Betz projection micromanometers of range 0-800 mm water and a resolution of 0.1 mm. Static pressure (relative to atmospheric) at the orifice plate was measured using a similar projection micromanometer.

Barometric pressure was obtained from a precision quartz pressure gauge and air humidity with a whirling hygrometer. Temperatures were measured by standard platinum resistance thermometers with a digital readout or mercury-in-glass thermometers. Most of the above instruments were calibrated prior to use and all are traceable to national standards.

4.3 Orifice Plates

Orifice plates of three diameter ratios were chosen for this investigation, viz 0.4, 0.6 and 0.75, typical of those in regular use. Thus the nominal orifice bores were 120, 180 and 225 mm respectively. The plates were machined in the NEL workshop from blanks supplied by the manufacturers of the junior orifice fitting. Measurements of orifice bore, concentricity, thickness, flatness and surface roughness were made immediately after manufacture to ensure that the plates conformed fully to the requirements of ISO 5167.

4.4 Edge Sharpness Measurement

The radii of the sharp edges of the orifice plates were measured repeatedly during the course of the project. Two different and complementary methods were used.

4.4.1 Stylus method

This method is based on a development of the well known 'Talysurf' roughness measuring machine, or its equivalent, which is used to measure the surface finish of plates. By reducing the sensitivity of the machine in the vertical direction to that in the horizontal, a sufficient range can be obtained to examine the edge. As the roughness of the surface is not of prime interest, and the sensitivity is reduced, it is unnecessary to use a pointed stylus. A small spherical ball, which can be manufactured and measured to fine tolerances, is commonly used, being less likely to wear, but of course due allowance must be made for the radius of the ball itself. Magnifications of up to 500 times have been successfully used.

4.4.2 Casting method

This method was developed by Gallacher[14] of NEL and is based on the use of casting resins. A liquid cold-forming plastic was poured into a wax or plasticine mould surrounding the location on the orifice plate to be measured. When hardened, the casting can be removed, sliced and polished to a reference line, thus forming a perfect replica of the original edge. Results accurate to 0.005 mm have been obtained.

For each plate the edge radius was measured at eight positions, equally distributed around the bore, by both the stylus method and using plastic replicas.

5 TEST PROGRAMME

5.1 Datum Calibrations

Every test orifice plate was calibrated in the 'as received' condition to provide a datum or reference calibration against which any subsequent changes could be measured. In doing the first few of these it was necessary to establish the amount of random variation experienced in making the measurements and determine the number of test points to be taken in order to keep the uncertainty to within a fraction of the changes that were anticipated in subsequent tests. A typical calibration for an 0.6 dia. ratio plate is shown in Fig. 2. In this case the discharge coefficient after initially decreasing with increasing Reynolds number became virtually constant above a throat Reynolds number of 5×10^5. Subsequent calibrations were made for the range of Reynolds number over which the discharge coefficient was sensibly constant.

For a set of results the mean discharge coefficient and the standard deviation can be determined. It was established that, if about 25 test points are taken, the standard deviation of the mean discharge coefficient is about 0.03 per cent. As differences in discharge coefficient as small as 0.1 per cent were being sought, this figure was deemed to be acceptable. Any further significant reduction in the standard deviation of the mean would have necessitated unrealistically large numbers of test points.

The results of the initial calibrations of all the test plates available at the beginning of the project are summarised in Table 1. In most cases the agreement between different plates of the same diameter ratio was very good. The mean value of discharge coefficient over a specified Reynolds number range was used as a basis for comparison.

5.2 Upstream Edge Sharpness Tests

The major part of the project was to investigate the effect of the sharpness of the upstream edge of the orifice plate on the discharge coefficient. Initially three plates, each of a different diameter ratio, were selected for this work. For the first set of calibrations a target radius of 0.0001d was specified. This lay in the range 10-20 µm (0.0005-0.001 in) and was about one-quarter of the limiting value specified in ISO 5167.

After the initial calibrations the edges of the plates were successively rounded, measured and the plates recalibrated. Edge sharpness measurements were made using both the stylus method and by means of plastic replicas. This procedure of rounding, measurement and calibration was repeated until five complete sets of data were obtained for each plate evenly spaced over the range of edge radii covered.

The results, plotted as the change in discharge coefficient from the datum against the ratio of the edge radius to bore diameter, are shown in Fig. 3. Apart from two points, which appear to be exceptionally high, there is a clear trend of gradually increasing discharge coefficient as the radius of the sharp edge increased. Further tests made on two additional plates with a small degree of rounding confirmed this trend.

5.3 Local Damage to Upstream Edge

In contrast to the work described in the previous section, these tests were designed to simulate the effects of foreign objects, eg a bolt, passing along the pipe and striking the edge of the orifice plate. To achieve this kind of damage it was necessary to damage the plate by an impact method. By this means the metal is not simply removed, but is displaced and small raised areas are formed around the site of the indentation.

The method actually adopted used a cold chisel held at about 45° to the face of the plate and which was then struck sharply with a hammer. The resulting damage is shown in Fig. 4.

Two additional orifice plates were damaged in this way and then recalibrated. Their diameter ratios were 0.34 and 0.75. In the case of the former, calibrations were carried out with the indentation both adjacent to and at right angles to the pressure tappings; see Table 2.

As the differences were very small, further tests were made using both plates with the notches successively deepened by filing until greater changes became evident. These will be correlated with the dimensions of the notch once the measurements are completed.

5.4 Effect of Downstream Face

In the initial proposal for the project it was intended to investigate the effects of scores and scratches at various positions on and of increasing roughness of the downstream face of the orifice plate upon the discharge coefficient. As small imperfections on the downstream face were not expected to have much effect it was decided to begin with an investigation of the increasing roughness of the face which seemed likely to have the greater influence.

One plate of each diameter ratio therefore had its downstream face roughened by gluing on coarse sandpaper. No significant change in discharge coefficient was obtained, see Table 3. Further tests indicated that it did not matter whether the roughness was present over the whole of the downstream face or simply on the downstream level.

Because it was feared that the effective increase in thickness of the orifice plate might have an influence as well as the roughness, a further test was carried out with a sheet of smooth thin material (about 1.5 mm thick) glued to the entire downstream face of the plate, there being no hole in the annulus initially. In this test a small reduction in the discharge coefficient was observed, but this was not significant.

Following this, some further tests were made, this time to simulate localised roughness. In the first series of these tests a small disc of the sandpaper (25 mm dia.) was glued to the downstream face to simulate a patch of corrosion. Calibrations were made with this disc both adjacent to the pressure tappings and at 90° to them. A small increase in discharge coefficient was observed when the disc was adjacent to the pressure tappings, but when it was at right angles to them no significant difference could be detected, see Table 4.

For the second series of tests the arrangement was reversed. The sandpaper with a 25 mm disc removed was glued on smooth side out, leaving a depression to simulate the effect of corrosion pitting. Calibrations were again made with the hollow at right angles to the pressure tappings and adjacent to them. Very small increases in the discharge coefficient were observed, that with the depression adjacent to the pressure tappings being the greater, see Table 5.

6 CONCLUSIONS

Experimental investigations have confirmed that the radius of the sharp edge of orifice plates has a marked effect upon the discharge coefficient. On the other hand, local damage to the sharp edge needs to be particularly severe before a significant change in the discharge coefficient is detected. Thus the requirements of the current standards which call for the rejection of plates showing any visible defects may be unnecessarily stringent.

A general and gross increase in the roughness of the downstream face did not appear to have any significant effect, but local roughness patches gave a small change, especially when aligned with one of the pressure tappings.

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LIST OF FIGURES

TABLE 1

INITIAL CALIBRATIONS

Plate No	Diameter ratio (nominal)	Diameter m	Mean discharge coefficient
1	0.75	0.228 94	0.6032
2	0.75	0.228 57	0.6032
3	0.75	0.228 55	0.6021
4	0.75	0.228 52	0.6031
5	0.6	0.183 24	0.6073
6	0.6	0.184 82	0.6071
7	0.6	0.184 84	0.6066
8	0.6	0.182 79	0.6073
9	0.4	0.122 21	0.6062
10	0.4	0.121 87	0.6056
11	0.4	0.121 88	0.6053
12	0.4	0.121 83	0.6056

TABLE 2

CALIBRATIONS WITH LOCAL SEVERE DAMAGE TO UPSTREAM EDGE

Calibration	Discharge coefficient	Per cent change
Diameter ratio B = 0.34		
Datum calibration	0.6047	-
Damage at 90° to tappings	0.6049	0.03
Damage adjacent to tappings	0.6058	0.18
Diameter ratio B = 0.75		
Datum calibration	0.6056	-
Damage adjacent to tappings (Stage 1)	0.6057	0.02
Damage adjacent to tappings (Stage 2)	0.6067	0.18

TABLE 3

CALIBRATIONS WITH ROUGH DOWNSTREAM FACE

Plate No	Diameter ratio	Initial C	Final C	Per cent change
1	0.75	0.6032	0.6040	0.133
7	0.6	0.6066	0.6068	0.033
9	0.4	0.6062	0.6067	0.083

TABLE 4

CALIBRATIONS WITH DISC OF SANDPAPER GLUED TO DOWNSTREAM FACE

Calibration	Discharge coefficient	Per cent change
Datum calibration	0.6062	-
Disc at 90° to tappings	0.6061	-0.02
Disc adjacent to tappings	0.6076	0.23

TABLE 5

CALIBRATIONS WITH A DEPRESSION ON DOWNSTREAM FACE

Calibration	Discharge coefficient	Per cent change
Datum calibration	0.6062	-
Hole at 90° to tappings	0.6069	0.12
Hole adjacent to tappings	0.6082	0.33

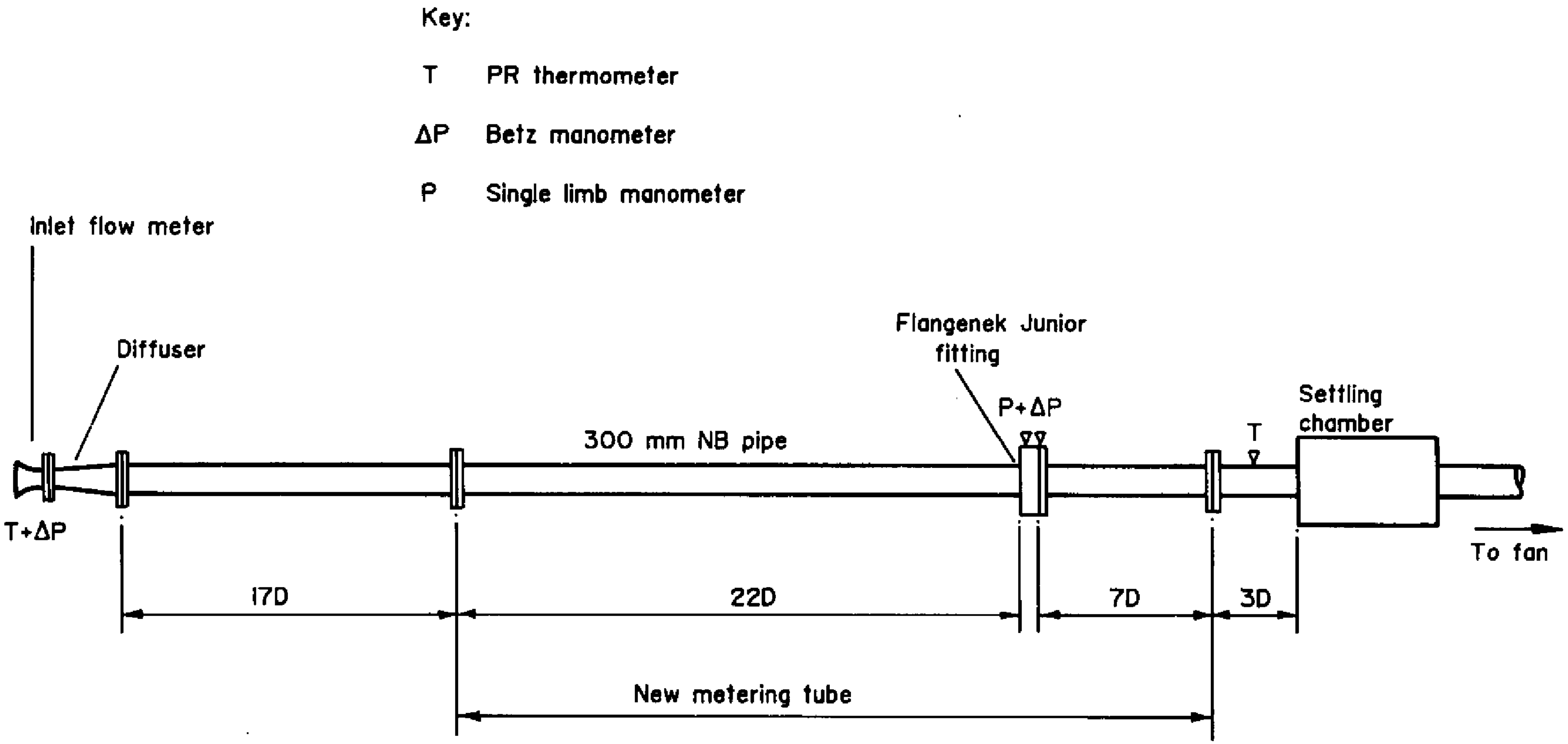


Fig 1 Layout of Calibration Line

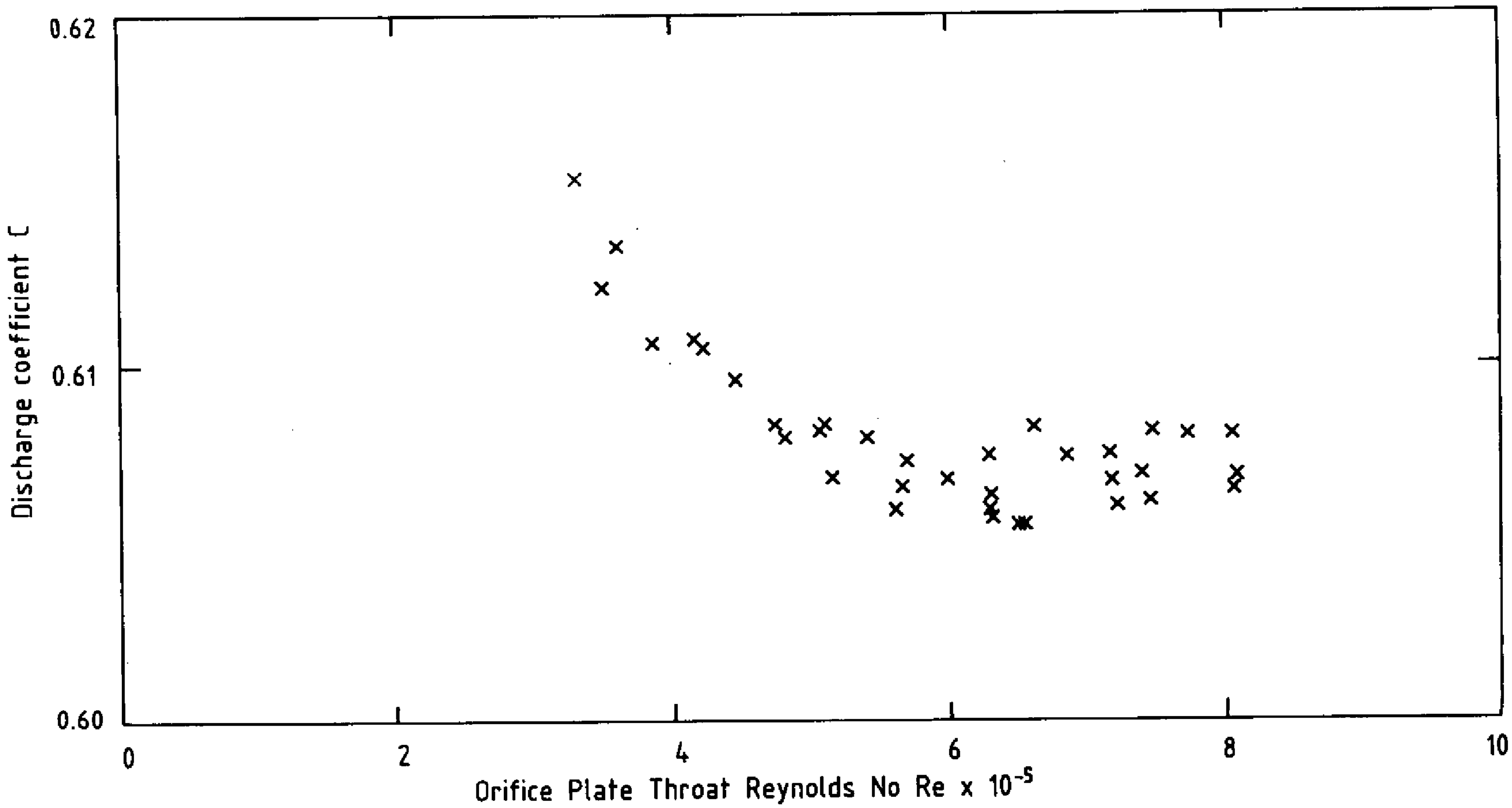


Fig 2 Typical Calibration of 0.6 Beta Plate

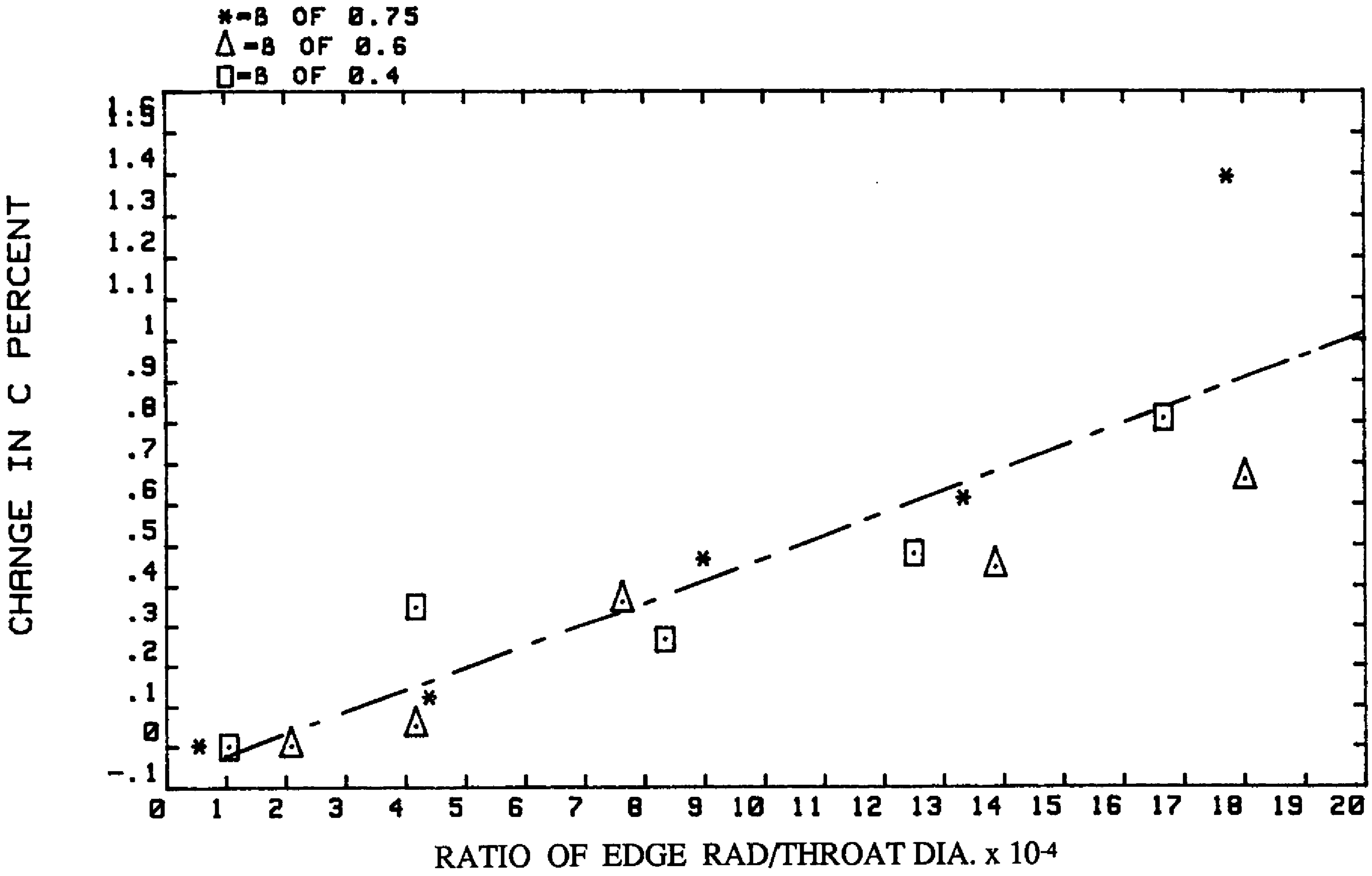
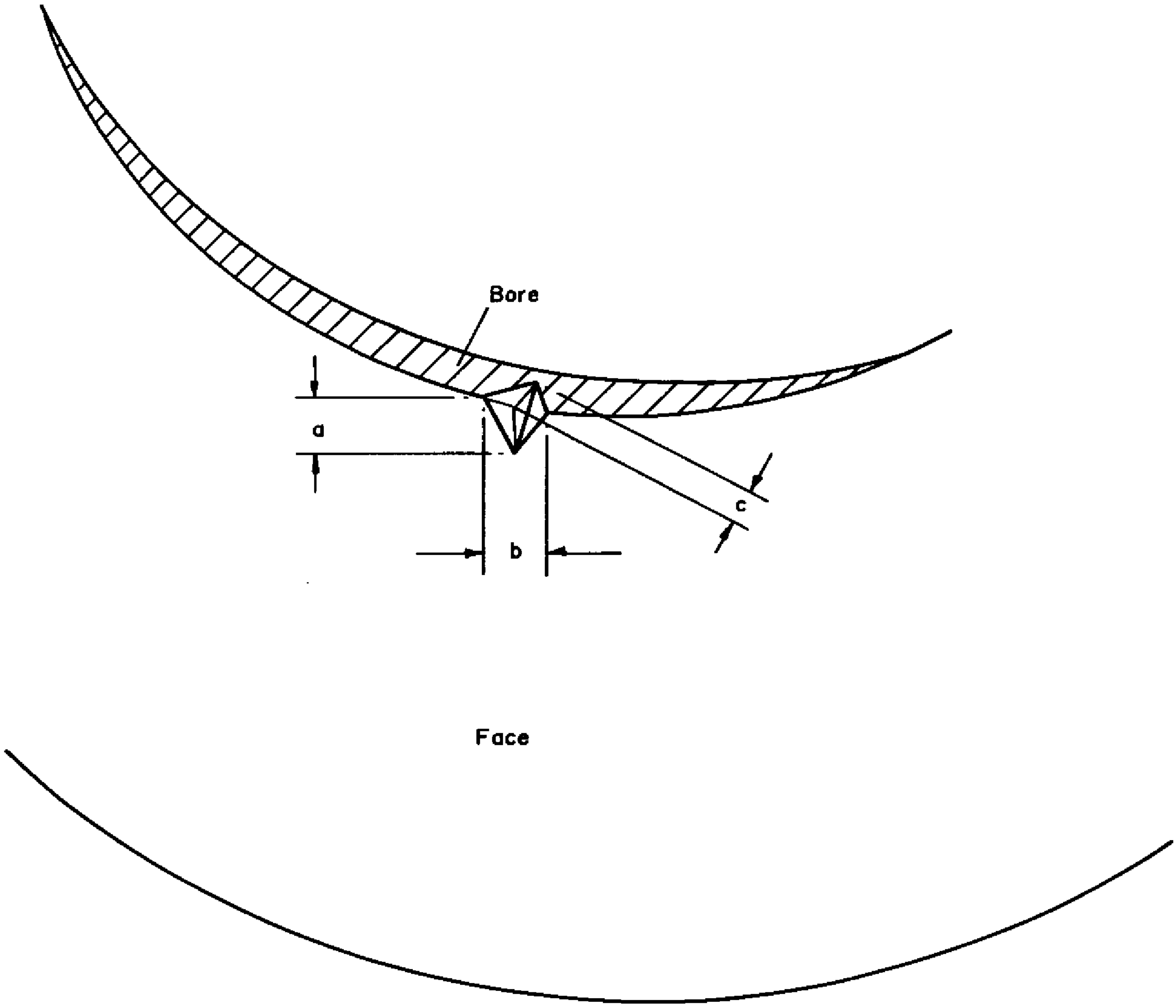


Fig 3 Effect of Edge Radius on Discharge Coefficient



Diameter ratio	Dimension (mm)		
	a	b	c
0.34	2.3	2.26	2.1
0.75	2.0	3.07	4.44

Fig 4 Geometry of Orifice Plate Damage