BRITISH STANDARD

BS 1042 : Section 1.5 : 1997

Incorporating Amendment No. 1

Measurement of fluid flow in closed conduits

Part 1. Pressure differential devices

Section 1.5 Guide to the effect of departure from the conditions specified in BS EN ISO 5167-1

ICS 17.120.10

Committees responsible for this British Standard

The preparation of this British Standard was entrusted to Technical Committee CPL/30, Measurement of fluid flow in closed conduits, upon which the following bodies were represented:

British Compressed Air Society
British Gas plc
Department of Energy (Gas and Oil Measurement Branch)
Department of Trade and Industry (National Engineering Laboratory)
Electricity Industry in United Kingdom
Energy Industries Council
GAMBICA (BEAMA Ltd.)
Institute of Measurement and Control
Institute of Petroleum
Institute of Trading Standards Administration
Institution of Gas Engineers
Institution of Mechanical Engineers
Society of British Gas Industries
Water Services Association of England and Wales

The following bodies were also represented in the drafting of the standard, through subcommittees and panels:

Engineering Equipment and Materials Users' Association
Institution of Water and Environmental Management
United Kingdom Offshore Operators' Association

This British Standard, having been prepared under the direction of the Sector Board for Materials and Chemicals, was published under the authority of the Standards Board and comes into effect on 15 June 1997

First published 1965
Second edition December 1987
Third edition June 1997

The following BSI references relate to the work on this standard:
Committee reference CPL/30
Draft for comment 95/208878 DC

ISBN 0 580 26822 5

Amendments issued since publication

Amd. No.	Date	Text affected
9933	March 1998	Indicated by a line in the margin

Contents

		Page
Committees responsible		Inside front cover
Foreword		iii
Guide		
Section 1. General		
Introduction		1
1.1	Scope	1
1.2	References	1
1.3	Symbols and definitions	1
1.4	Effect of errors on flowrate calculations	3
Section 2. Effects of deviations in construction		
2.1	Orifice plate edge sharpness	4
2.2	Thickness of orifice edge	4
2.3	Condition of upstream and downstream faces of orifice plate	4
2.4	Position of pressure tappings for an orifice meter	4
2.5	Condition of pressure tappings	7
Section 3. Effects of pipeline near meter		
3.1	Pipe diameter	8
3.2	Steps and taper sections	8
3.3	Diameter of carrier ring	8
3.4	Under size joint rings	8
3.5	Protruding welds	8
3.6	Eccentricity	12
Section 4. Effects of pipe layout		
4.1	General	16
4.2	Discharge coefficient compensation	16
4.3	Pressure tappings	16
4.4	Devices for improving flow conditions	16
Section 5. Operational deviations		
5.1	General	20
5.2	Deformation of an orifice plate	20
5.3	Deposition of the upstream face of an orifice plate	22
5.4	Deposition in the meter tube	22
5.5	Deposition and increase of surface roughness in Venturi tubes	22
5.6	Orifice plate edge sharpness	22
Section 6. Pipe roughness		
6.1	General	26
6.2	Upstream pipe	26
6.3	Downstream pipe	26
6.4	Reduction of roughness effects	28
6.5	Maintenance	28
Annexes		
A	Bibliography	30

Page

Tables

1	Symbols	2
2	Effect of taper pieces	9
3	Percentage discharge coefficient changes *(c)* when the straight pipe lengths before the orifice are less than specified in BS EN ISO 5167-1	17
4	Formulae for additional uncertainty in the orifice discharge coefficient, to be used with the percentage changes given in table 3, for all tapping arrangements	18
5	Minimum E/D_2 ratios for orifice plates manufactured in AISI 304 or 316 stainless steel	20
6	Effect of deposits on $\beta = 0.2$ and $\beta = 0.7$ orifice plates	23
7	Values of n, U/u_{CL} and λ for smooth pipe	26
8	Values of n, U/u_{CL} and λ for rough pipe	26
9	Recommendations regarding the extent of cleaning	29

Figures

1	Effect of edge radius on discharge coefficient	5
2	Change in discharge coefficient as a function of orifice thickness	6
3	Carrier having internal diamter D_1 less than pipe diameter D	10
4	Effect of incorrect carrier diameter	11
5	Possible orifice plate eccentricity resulting from specified tolerances on bolt hole, bolt hole pitch circle, pipe o.d. and flange bore	13
6	Discharge coefficient error vs eccentricity for an orifice plate with D and $D/2$ and flange taps	14
7	Triple-T arrangements	15
8	The NEL flow conditioner	18
9	Flow straightner installation	19
10	Effect of orifice place deformation on flow measurement accuracy	21
11	Effect of welding rods in meter tube	24
12	Effect of debris in meter tube (on both sides of plate)	24
13	Variation of Venturi meter coefficient with surface roughness	25
14	The effect of rough pipe on discharge coefficient	27
15	The combined effect of abnormal roughness and diminution in pipe bore	27
16	The effect of abnormal roughness on orifice plates	28

List of references Inside back cover

Foreword

This Section of BS 1042 has been prepared by Technical Committee CPL/30. It supersedes BS 1042 : Section 1.5 : 1987, which is withdrawn.

This revision of BS 1042 Section 1.5 was prepared in order to bring it up-to-date with BS EN ISO 5167-1 : 1992 (formerly BS 1042 : Section 1.1) to which it refers, and to incorporate new data.

This Section of BS 1042 : Part 1 is one of a series dealing with measurement of fluid flow by differential pressure devices, as follows: BS EN ISO 5167-1 *Specification for square-edged orifice plates, nozzles and Venturi tubes in circular cross-section conduits running full.*

BS 1042 : Part 1 : Section 1.2 *Specification for square-edged orifice plates and nozzles (with drain holes, in pipes below 50 mm diameter, as inlet and outlet devices) and other orifice plates.*

BS EN ISO 9300 *Method of measurement of gas flow by means of critical flow Venturi nozzles.*

BS 1042 : Part 1 : Section 1.4 *Guide to the use of devices specified in Sections 1.1* (i.e. BS EN ISO 5167-1) and 1.2.

Section 1.5 *Guide to the effect of departure from the conditions specified in BS EN ISO 5167-1.*

Section 1.6 *Method of measurement of pulsating fluid flow in a pipe, by means of orifice plates, nozzles or Venturi tubes.*

BS 1042 : Section 1.4 contains an index to Sections 1.2 and 1.4 and to BS EN ISO 5167-1, to facilitate the rapid cross-referencing of subject matter.

As a Guide, this British Standard takes the form of guidance and recommendations. It should not be quoted as if it were a specification and particular care should be taken to ensure that claims of compliance are not misleading.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

blank

Section 1. General

Introduction

BS EN ISO 5167-1 is a standard for flowrate measurement using a differential pressure device. Adherence to that standard will result in flowrate measurements the uncertainty of which will lie within specified limits. If, however, a flowmetering installation departs, for whatever reason, from the conditions specified in BS EN ISO 5167-1, the specified limits of uncertainty may not be achieved. Many metering installations exist where these conditions either have not been or cannot be met. In these circumstances it is usually not possible to evaluate the precise effect of any such deviations. However, a considerable amount of data exists which can be used to give a general indication of the effect of non-conformity to BS EN ISO 5167-1, and it is presented here as a guide to users of flow metering equipment.

1.1 Scope

This Section of BS 1042 provides guidance to assist in estimating the flowrate when using pressure differential devices constructed or operated outside the scope of BS EN ISO 5167-1.

It should not be inferred that additional tolerances or corrections can necessarily compensate for the effects of deviating from the standard. The information is given, in the first place, to indicate the degree of care necessary in the manufacture, installation and maintenance of pressure differential devices by describing some of the effects of non-conformity to the requirements; and in the second place, to permit those users who may not be able to comply fully with the requirements to assess, however roughly, the magnitude and direction of the resulting error in flowrate.

Each variation dealt with is treated as though it were the only one present. Where more than one is known to exist, there may be unpredictable interactions and care has to be taken when combining the assessment of these errors. If there is a significant number of errors, means of eliminating some of them must be considered. The variations included in this standard are by no means complete and relate largely to examples with orifice plates. There are, no doubt, many similar examples of installations not conforming to BS EN ISO 5167-1 for which no comparable data have been published. Such additional information from users, manufacturers and any others may be taken into account in future revisions of this Section of BS 1042.

1.2 References

1.2.1 Normative references

This standard incorporates, by dated or undated reference, provisions from other publications. These normative references are made at the appropriate places in the text and the cited publications are listed on the inside back cover. For dated references, only the edition cited applies; any subsequent amendments to or revisions of the cited publication apply to this Section of BS 1042 only when incorporated in the reference by amendment or revision. For undated references, the latest edition of the cited publication applies, together with any amendments.

1.2.2 Informative references

This standard refers to other publications that provide information or guidance. Editions of these publications current at the time of issue of this standard are listed on the inside back cover, but reference should be made to the latest editions.

1.3 Symbols and definitions

1.3.1 Symbols

For the purposes of this Section of BS 1042, the symbols given in table 1 apply.

1.3.2 Definitions

For the purposes of this Section of BS 1042, the definitions given in BS EN ISO 5167-1 apply, together with the following.

1.3.2.1 square edge

The angular relationship between the orifice bore and the upstream face, when the angle between them is $90^\circ \pm 0.3^\circ$.

1.3.2.2 sharpness

The radius of the edge between the orifice bore and the upstream face.

NOTE. The upstream edge of the orifice bore is considered to be sharp when its radius is not greater than 0.0004 d, where d is the diameter of the orifice bore.

Table 1. Symbols

Symbol	Represented quantity	Dimensions M: mass L: length T: time	SI units
c	Percentage change in discharge coefficient $\left(\equiv 100\,\frac{\Delta C}{C}\right)$	dimensionless	
C	Discharge coefficient	dimensionless	
C_c	Contraction coefficient	dimensionless	
d	Diameter of orifice or throat of primary device at operating conditions	L	m
D	Upstream internal pipe diameter at operating conditions	L	m
D_1	Carrier ring diameter	L	m
D_2	Orifice plate support diameter	L	m
e	Relative uncertainty	dimensionless	
E	Orifice plate thickness	L	m
E_e	Thickness of orifice	L	m
k	Uniform equivalent roughness	L	m
L_1	Distance of upstream pressure tapping from upstream face of plate divided by pipe bore (D)	dimensionless	
L_2'	Distance of downstream pressure tapping from downstream face of plate divided by pipe bore (D)	dimensionless	
q_m	Mass rate of flow	MT^{-1}	kg/s
r	Orifice plate edge radius	L	m
Re_D	Reynolds number based on upstream pipe diameter	dimensionless	
Re_d	Reynolds number based on throat bore of device	dimensionless	
$S_{L,1}$	Distance from upstream fitting to straightener	L	m
$S_{L,2}$	Distance from straightener to primary device	L	m
$S_{L,3}$	Distance from primary device to downstream fitting	L	m
u	Local axial velocity	LT^{-1}	m/s
u_{CL}	Centre line axial velocity	LT^{-1}	m/s
U	Mean axial velocity	LT^{-1}	m/s
Y	Modulus of elasticity of orifice plate material	$ML^{-1}T^{-2}$	Pa
β	Diameter ratio, $\beta = d/D$	dimensionless	
Δp	Differential pressure	$ML^{-1}T^{-2}$	Pa
Δp_y	Differential pressure required to reach orifice plate yield stress	$ML^{-1}T^{-2}$	Pa
ε_1	Expansibility (expansion) factor at the upstream pressure tapping	dimensionless	
λ	Friction factor	dimensionless	
ρ	Fluid density	ML^{-3}	kg/m^3
ρ_1	Fluid density at the upstream pressure tapping	ML^{-3}	kg/m^3
σ_y	Yield stress of orifice plate material	$ML^{-1}T^{-2}$	Pa

1.4 Effect of errors on flowrate calculations

1.4.1 General

In this Section of BS 1042 the effects of deviations from the conditions specified in BS EN ISO 5167-1 are described in terms of changes in the discharge coefficient of the meter. The discharge coefficient of a pressure differential device (C) is given by the following equation:

$$C = \frac{4\, q_\mathrm{m} \sqrt{(1 - \beta^4)}}{\varepsilon_1\, \pi\, d_2 \sqrt{(2 \Delta \mathrm{p} \rho_1)}}$$

The sharp edge of an orifice plate ensures separation of the flow and consequently contraction of the fluid stream to the vena contracta. Defining the contraction coefficient,

$$C_\mathrm{c}, \text{ as } \frac{\text{flow area}}{\text{geometric area}},$$

the orifice produces $C_\mathrm{c} \simeq 0.6$, which mainly accounts for the discharge coefficient, $C \simeq 0.6$.

The effect of change in the discharge coefficient is illustrated by the following example.

Consider an orifice plate with an unduly rounded edge. The result of this will be to reduce the separation and increase C_c, leading in turn to reduced velocities at the vena contracta. The observed differential pressure will therefore decrease. From the equation above, it can be seen that the discharge coefficient would therefore increase. Alternatively, as C_c increases so does C. If no correction is made for this change in C, the meter will under-read (register).

It can therefore be concluded that:

a) an effect which causes an increase in discharge coefficient will result in an under-reading of flow if the coefficient is not corrected; and conversely,

b) an effect which causes a decrease in discharge coefficient will result in an over-reading of flow if the coefficient is not corrected.

1.4.2 Quantifiable effects

When the user is aware of such effects and they can be quantified, the appropriate discharge coefficient can be used and the correct flowrate calculated. However, the precise quantification of these effects is difficult and so any flowrate calculated in such a manner should be considered to have an increased uncertainty.

Except where otherwise stated, an additional uncertainty factor, equivalent to 100 % of the discharge coefficient correction, should be added arithmetically to that of the discharge coefficient when estimating the overall uncertainty of the flowrate measurement.

Section 2. Effects of deviations in construction

2.1 Orifice plate edge sharpness

Orifice plates that do not have the specified sharpness of the inlet edge (edge radius $r \leq 0.0004\,d$ in accordance with **8.1.6.2** of BS EN ISO 5167-1 : 1992), will have progressively increasing discharge coefficients as the edge radius increases. Tests have shown that the effect on the discharge coefficient, C, is to increase it by 0.5 % for r/d of 0.001, and by about 5 % for r/d of 0.01. This is an approximately linear relationship (see figure 1 and Hobbs and Humphreys[1]). These values apply particularly to Re_d values above 300 000 and for β values below 0.7, but they can be used as a general guide for other values.

Measurement techniques for edge radius are available, but in general it is better to improve the edge sharpness to the required value rather than attempt to measure it and make appropriate corrections.

2.2 Thickness of orifice edge

For orifice plates, the increase in discharge coefficient due to the excessive thickness of the orifice edge (see **8.1.4** of BS EN ISO 5167-1 : 1992) can be appreciable. With a straight bore orifice plate in a 150 mm pipe, the changes in discharge coefficient shown in figure 2 were obtained (see Husain and Teyssandier [2]).

2.3 Condition of upstream and downstream faces of orifice plate

The upstream face should be flat and smooth. Excessive roughness leads to an increase in the discharge coefficient. Tests have indicated that a surface roughness of $0.0003\,d$ will cause an increase in discharge coefficient of the order of 0.1 %. Since the requirement for edge sharpness is $r \leq 0.0004\,d$, an increase in plate roughness will make it difficult to define or confirm that the sharp edge requirement has been met.

Local damage to the upstream face or edge of an orifice plate does not adversely affect the discharge coefficient provided that the damage is kept as far away from the pressure tapping as possible (see Hobbs and Humphreys [1]). The discharge coefficient is much less sensitive to the surface condition of the downstream face of the plate (Hobbs and Humphreys[1]).

Large scale lack of flatness, e.g. 'dishing', leads to flow measurement errors. A 'dishing' of 1 % in the direction of flow will cause an under-reading, i.e. an increase in C, of about 0.2 % for $\beta = 0.2$ and about 0.1 % for $\beta = 0.7$. Distortion against the direction of flow also causes errors which could be either positive or negative depending on the amount of distortion.

2.4 Position of pressure tappings for an orifice meter

2.4.1 General

Values of the orifice plate discharge coefficient for the three standard tapping positions (corner, flange, D and $D/2$) can be calculated using the Stolz equation (see **8.3.2.1** of BS EN ISO 5167-1 : 1992). Where the tapping positions fall outside the tolerances permitted in BS EN ISO 5167-1 for the three positions, the discharge coefficient may be estimated as described in **2.4.2**. It should be emphasized that an additional uncertainty factor needs to be associated with the use of non-standard tapping positions.

2.4.2 Calculation of discharge coefficient

2.4.2.1 Calculate the actual values of L_1 and L_2'. The discharge coefficient can be estimated only if $L_1 \leq 1$ and $L_2' \leq 0.47$.

2.4.2.2 Using the actual values of L_1 and L_2', estimate the discharge coefficient using the Stolz equation.

2.4.3 Estimation of additional uncertainty

2.4.3.1 If tappings lie between the flange and corner taps, the additional uncertainty (e), expressed as a percentage, can be estimated from:

$$e = 25 \left| \frac{C_{FL}}{C_{CT}} - 1 \right| \quad (2)$$

where

C_{FL} is the discharge coefficient for flange taps;

C_{CT} is the discharge coefficient for corner taps.

2.4.3.2 If tappings lie between D and $D/2$ and flange taps, the additional uncertainty (e), expressed as a percentage, can be estimated from:

$$e = 25 \left| \frac{C_{D\text{ AND }D/2}}{C_{FL}} - 1 \right| \quad (3)$$

where

$C_{D\text{ AND }D/2}$ is the discharge coefficient for D and $D/2$ taps.

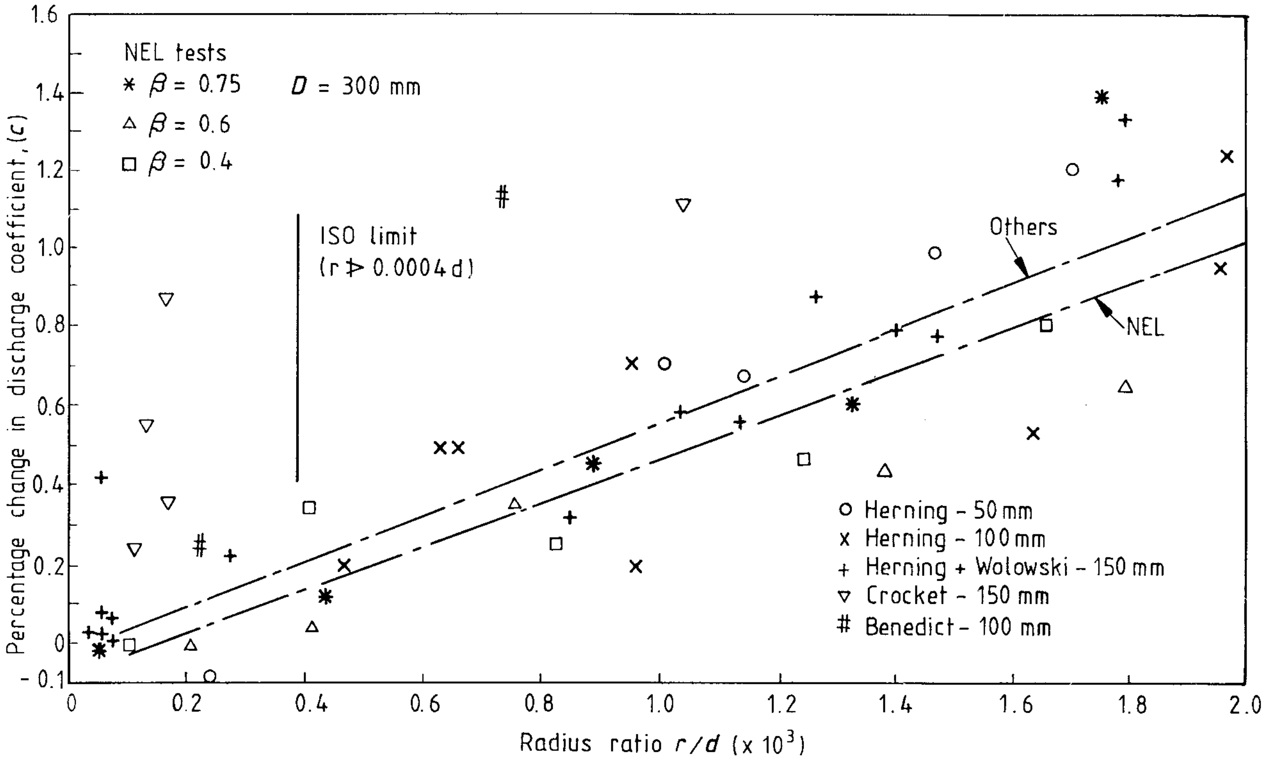


Figure 1. Effect of edge radius on discharge coefficient

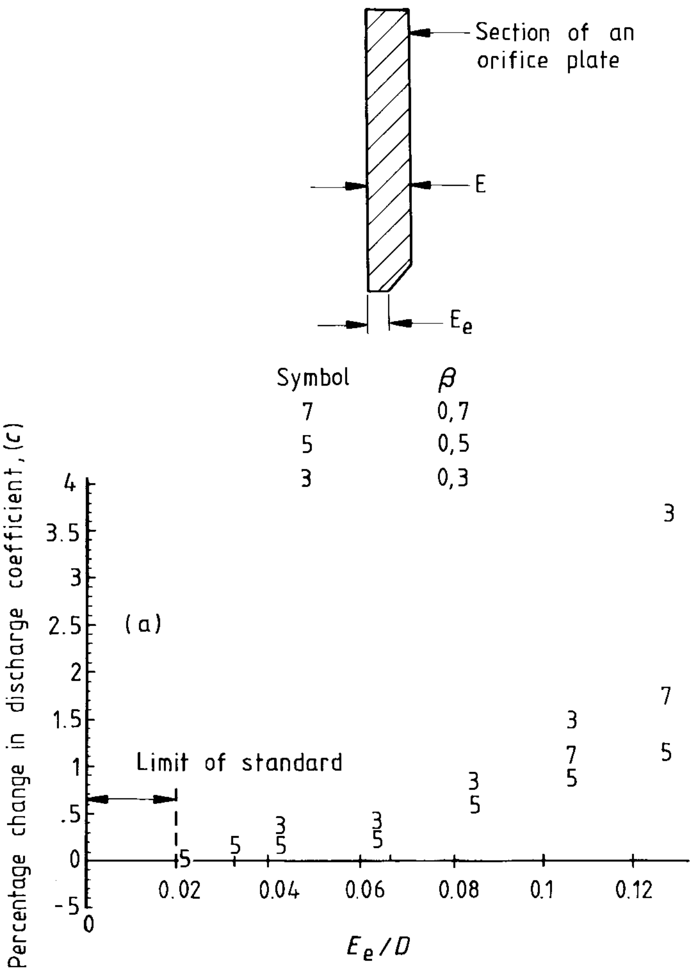


Figure 2. Change in discharge coefficient as a function of orifice thickness

2.4.4 Example

Consider an orifice meter with $\beta = 0.6$, $Re_D = 10^6$, $D = 254$ mm and tappings at 0.15 D upstream and downstream of the plate.

To estimate the discharge coefficient, use the Stolz equation with $L_1 = L_2' = 0.15$.

The tappings in this example lie between the flange and D and D/2 tapping positions. From tables A8 and A2 respectively of BS EN ISO 5167-1 : 1992:

$$C_{FL} = 0.6049$$

$$C_{D \text{ AND } D/2} = 0.6067$$

therefore, additional uncertainty

$$= 25 \left| \frac{0.6067}{0.6049} - 1 \right| \% \qquad (4)$$

$$= 0.074\ \%$$

The uncertainty of the discharge coefficient is 0.6 % (see **8.3.3.1** of BS EN ISO 5167-1 : 1992);

therefore, overall uncertainty = 0.6 + 0.074 ≈ 0.7 % (i.e. the uncertainty has been simply added arithmetically).

2.5 Condition of pressure tappings

Experience has shown that large errors can be created by pressure tappings which have burrs or deposits on, or close to, the edge where the tapping penetrates the pipe wall. This is particularly the case where the tapping is in the main flow stream such as throat taps in nozzles or venturi tubes, where quite small burrs can give rise to significant percentage errors. Upstream corner tappings and downstream tappings in relatively dead zones are much less susceptible to this problem.

The installation should be inspected before use and at regular intervals to ensure that these anomalies are not present.

Section 3. Effects of pipeline near the meter

3.1 Pipe diameter

The internal diameter of the pipe upstream and downstream of the primary device should always be measured to ensure that it is in accordance with **7.5** and **7.6** of BS EN ISO 5167-1 : 1992. Errors in the upstream internal diameter measurement will cause errors in the calculated rate of flow, which are given by:

$$\frac{\delta q_m}{q_m} = \frac{-2\,\beta^4}{(1-\beta^4)} \cdot \frac{\delta D}{D} \qquad (5)$$

These errors become significant for large β, e.g. with $\beta = 0.75$, a positive 1 % error in D will cause a negative 1 % error in q_{m}.

The downstream pipe is far less critical, as its diameter need only be within 3 % of that of the upstream pipe (see **7.5.1.6** of BS EN ISO 5167-1 : 1992).

3.2 Steps and taper sections

Sudden enlargements of the pipe in the vicinity of the primary device should always be avoided as large errors in flow measurement result from their use. Similarly, tapering sections of pipe can lead to significant errors, as can be seen from table 2 which gives the order of errors to be expected when an orifice plate with corner tappings is immediately preceded or followed by a taper piece.

From table 2 it will be seen that a taper piece divergent in the direction of flow, and placed immediately upstream, is not recommended, since discharge coefficient increases of up to 50 % are caused. On the other hand, a convergent taper piece, whether installed before or after the orifice plate, and provided it is not of a steeper angle than those shown, results in coefficient changes of generally less than 2 %.

3.3 Diameter of carrier ring

The requirements concerning the sizing and concentric mounting of carrier rings for orifice plates and nozzles are specified in **7.5.1.3**, **7.5.1.4**, **7.5.2.3**, **7.5.2.4** and figure 6 of BS EN ISO 5167-1 : 1992. If the requirement of **7.5.2.4** (i.e. that the centred carrier ring should not protrude into the pipe) is not met, relatively large flow measurement errors will be introduced. Figure 3 shows such an installation and figure 4, using the same notation, shows the approximate errors introduced for the given conditions. It is emphasized that in arriving at these errors, the internal diameter of the carrier ring, D_1, and not the diameter of the main line, has been used in determining the calculated flowrate and is to be used for D in determining the correction factor when making use of the values shown.

Where the carrier is oversize, experimental results indicate that for $\beta = 0.74$, a carrier 11 % oversize and extending 0.05 D upstream from the plate increased the discharge coefficient by approximately 0.5 %. However, for a similar geometry but with $\beta = 0.63$, no effect was found.

3.4 Undersize joint rings

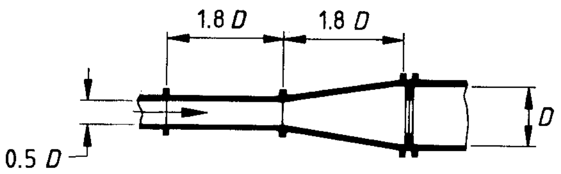
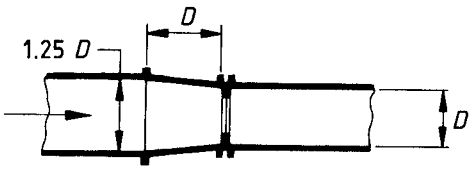
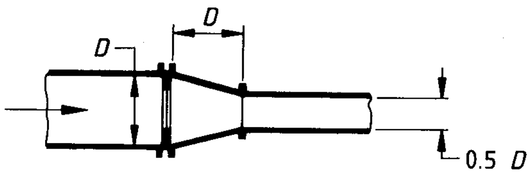
When the inside diameter of a joint ring or gasket is smaller than the pipe diameter, especially on the upstream side of an orifice plate or nozzle, very large flow measurement errors may occur. The magnitude and sign of the effect in relation to the measurement of flowrate is dependent on the combination of a number of variables, e.g. the thickness of the joint ring upstream of the orifice plate, the extent of its protrusion into the flow, its position relative to the orifice plate and pressure tappings, as well as on the degree of roughness of the upstream pipe.

3.5 Protruding welds

The effect of an undressed circumferential weld protruding into the pipe bore adjacent to the primary device will be similar to that of an undersize joint ring. Such an effect may arise from the fitting of a weld-neck flange, and the magnitude of the effect will depend on the height uniformity, or otherwise, of the protruding weld, and its position in relation to the single or multiple pressure tapping arrangement employed to measure the differential pressure across the primary device. To quantify the resulting error in a specific situation is difficult without a direct calibration.

From **7.1.5** in BS EN ISO 5167-1 : 1992 it should be noted that 'seamed pipe may be used provided that the internal weld bead is parallel to the pipe axis throughout the length of the pipe and satisfies the special requirements for the type of primary element. The seam shall not be situated in any sector of $\pm 30^\circ$ centred on any pressure tapping'.

Table 2. Effect of taper pieces

Position of orifice plate	β	**Order of the discharge coefficient change to be expected** %
a) Immediately downstream from a divergent taper piece 	0.4 0.7	+10 +50
b) Immediately downstream from a convergent taper piece 	0.4 0.7	−0.5 −2
c) Immediately upstream from a convergent taper piece 	0.4 0.7	0 to −1 +1

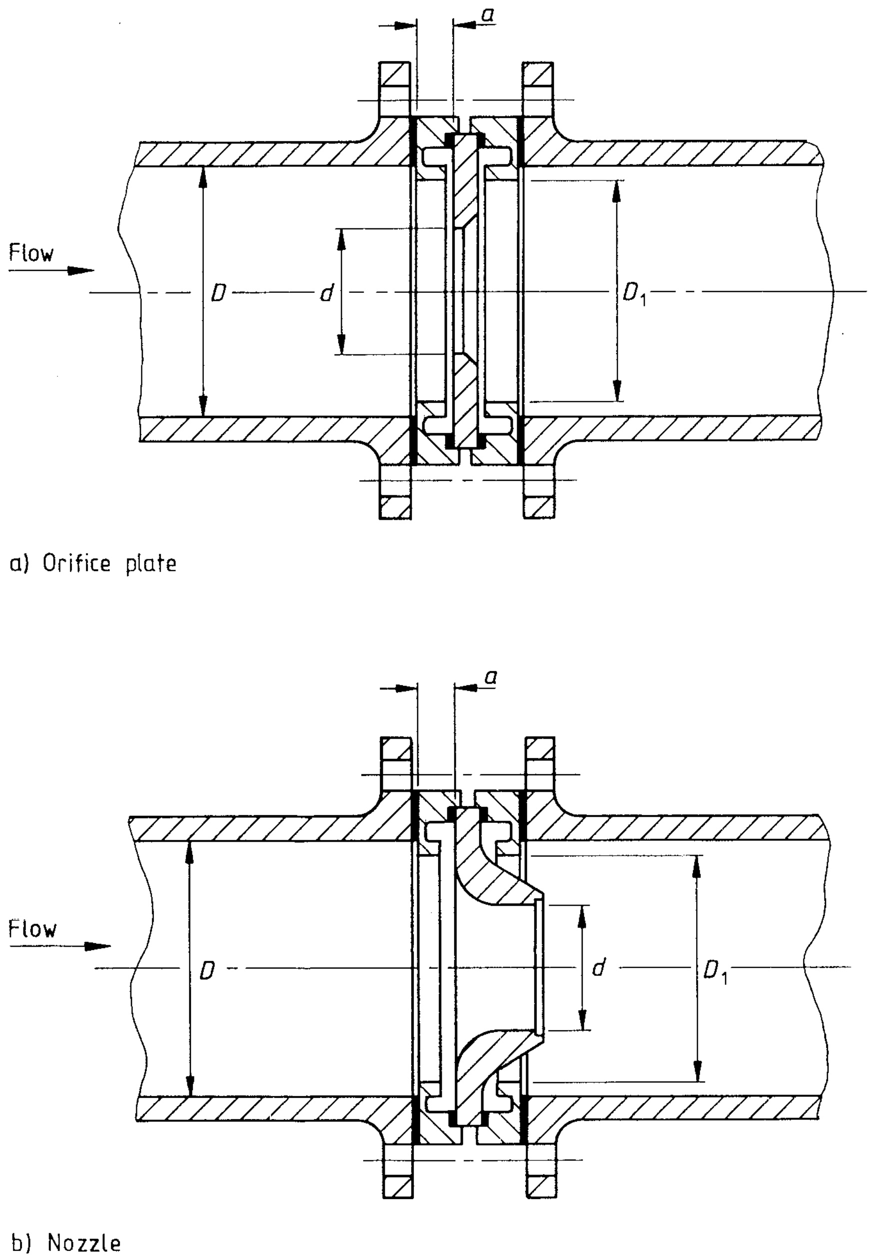


Figure 3. Carrier having internal diameter, D_1, less than pipe diameter, D

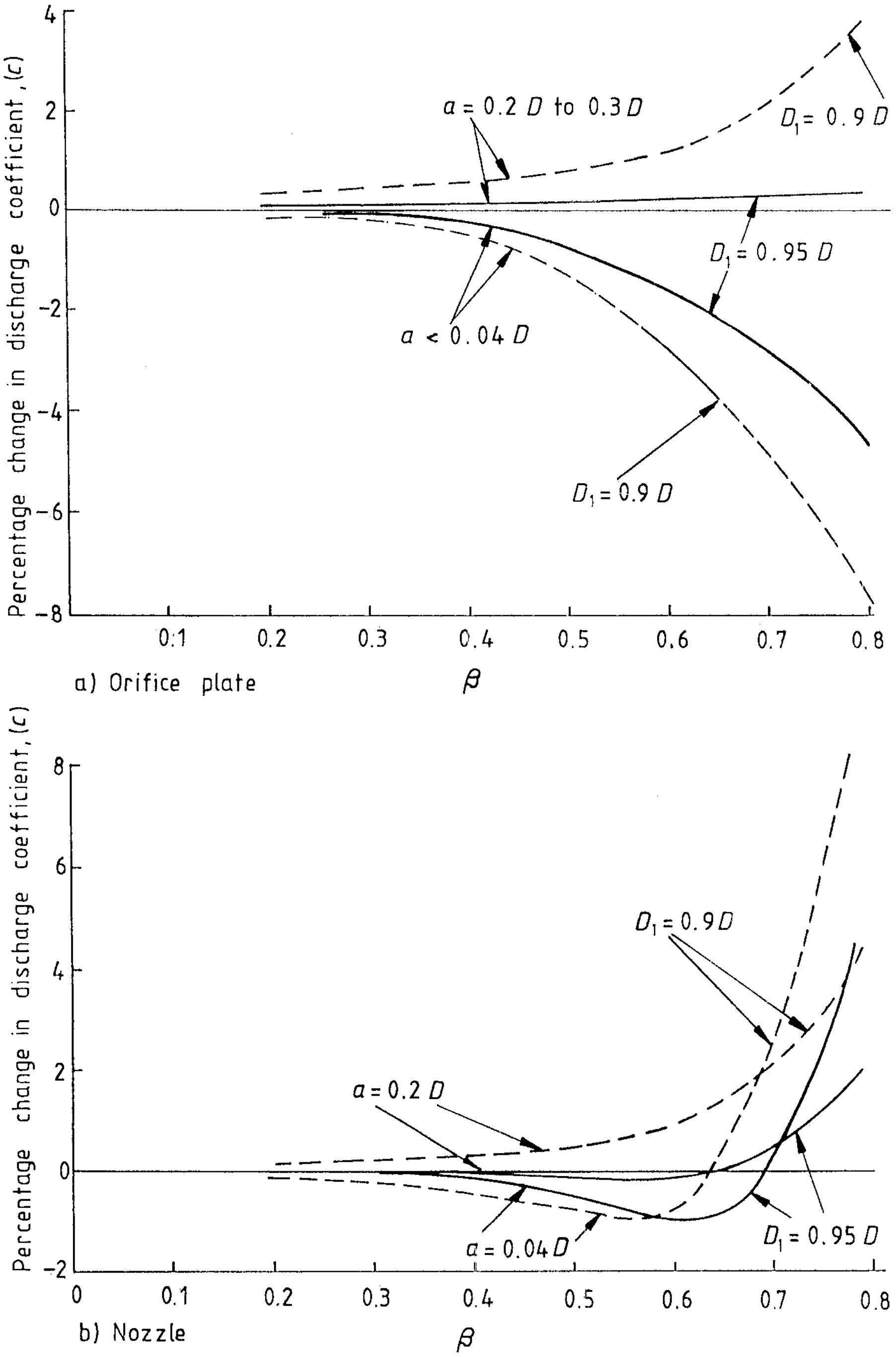


Figure 4. Effect of incorrect carrier diameter

3.6 Eccentricity

The requirements for concentric mounting of the device are given in **7.5.2.3**, **7.5.2.4** and **7.6.3** of BS EN ISO 5167-1 : 1992. The geometric measure of eccentricity is the distance between the pipe and orifice plate centre-lines and is often expressed as a percentage of the pipe diameter *D*. Deviations from the permitted eccentricity values for the mounting of an orifice plate relative to the upstream and downstream pipe sections will result in errors in the measurement flowrate. Figure 5 shows the eccentric mounting of an orifice plate in a sideways direction relative to the upstream pipeline. The displacement is to the right and the eccentricity is a combination of the dimensional tolerances arising from the bolt hole pitch circle diameter, the bolt diameter, the bolt hole diameter and the outer diameter of the orifice plate.

Experimental evidence on the effects of eccentricity is limited, but it has been shown that for orifice plates, the effect on discharge coefficient is a function of β, pipe size and roughness, pressure tapping type, location and magnitude, as well as the position of the orifice centre relative to the pressure tapping.

Experimental work indicates that the errors due to eccentricity increase in general with β. For $\beta = 0.2$ and eccentricity up to 5 % of *D*, discharge coefficient increases are unlikely to exceed 0.1 %. For larger β, the changes are best shown graphically as in figure 6.

Below 3 % eccentricity, the error varies with type of taps and direction of eccentricity. The meter is least sensitive to eccentricity perpendicular to the taps. Above 3 % eccentricity, errors for all taps and directions increase rapidly.

BS EN ISO 5167-1 requires an arithmetic increase in discharge coefficient uncertainty of 0.3 % if the eccentricity lies between:

$$\frac{0.0025D}{0.1 + 2.3\,\beta^4} \text{ and } \frac{0.005D}{0.1 + 2.3\,\beta^4} \qquad (6)$$

NOTE. No data are available for corner taps but the errors are probably similar to those for flange taps since the above data were obtained from a test line with $D = 150$ mm.

A further effect of eccentric positioning of an orifice plate is an increased unsteadiness of the differential pressure signal obtained. Observations have shown, for example, a marked increase in differential pressure reading fluctuations with increasing eccentricity for all values of β between 0.4 and 0.7.

Because of the number of variants contributing to the effect of eccentricity on the measurement of flow, the effect is difficult to quantify. Every effort should be made to restrict eccentricity to less than 3 % of *D*, particularly in the direction of the taps.

The effect may be minimized by employing four equally-spaced upstream and downstream taps on the flowmeter, as illustrated in figure 7. The pressure lines from these are then coupled in the widely used triple-T tapping arrangement in order to obtain an average differential pressure reading.

As a general guide, it may be assumed that the effects of eccentric mounting for multi-tapped nozzles will be less than those for orifice plates of equivalent β. Venturi tubes are less likely to be installed off-centre.

NOTE. Combined installation faults: it is recommended that errors arising from the combined effects of eccentricity, carrier ring steps etc. are not taken into account additively. The total possible error will be governed by the strongest of the effects present.

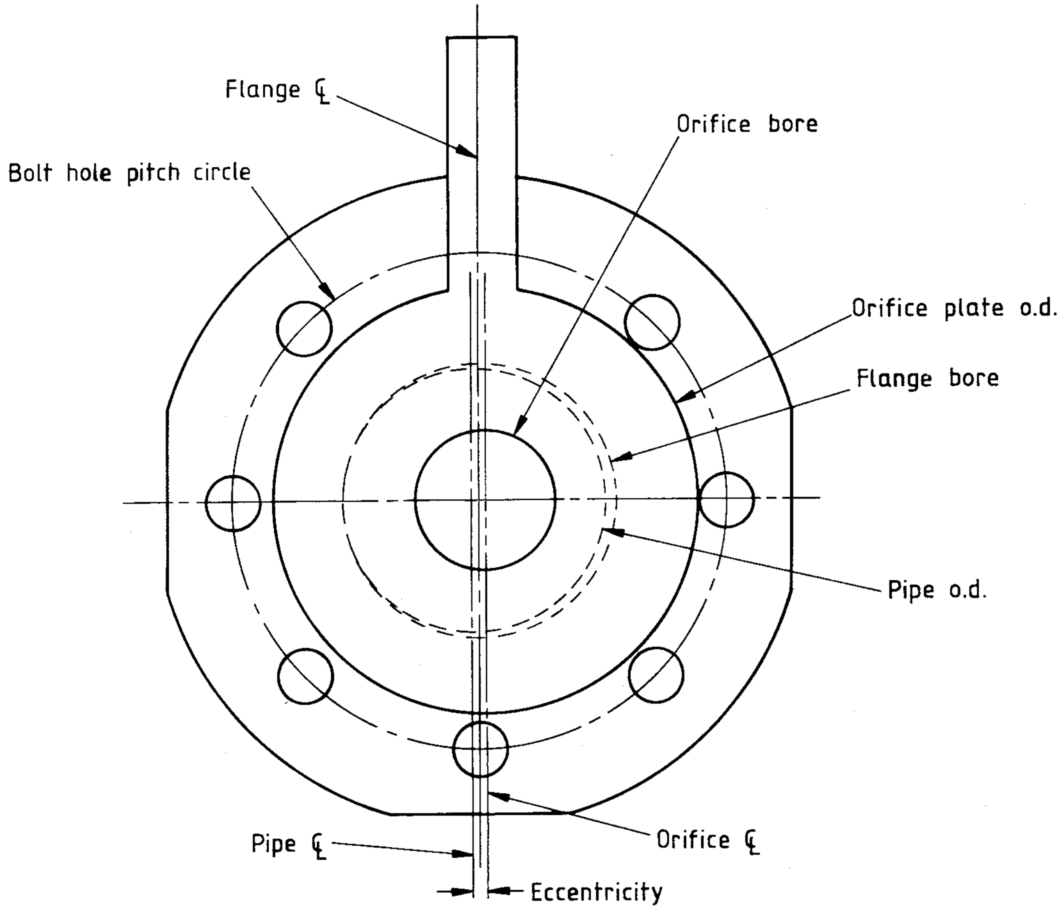


Figure 5. Possible orifice plate eccentricity resulting from specified tolerances on bolt hole, bolt hole pitch circle, pipe o.d. and flange bore

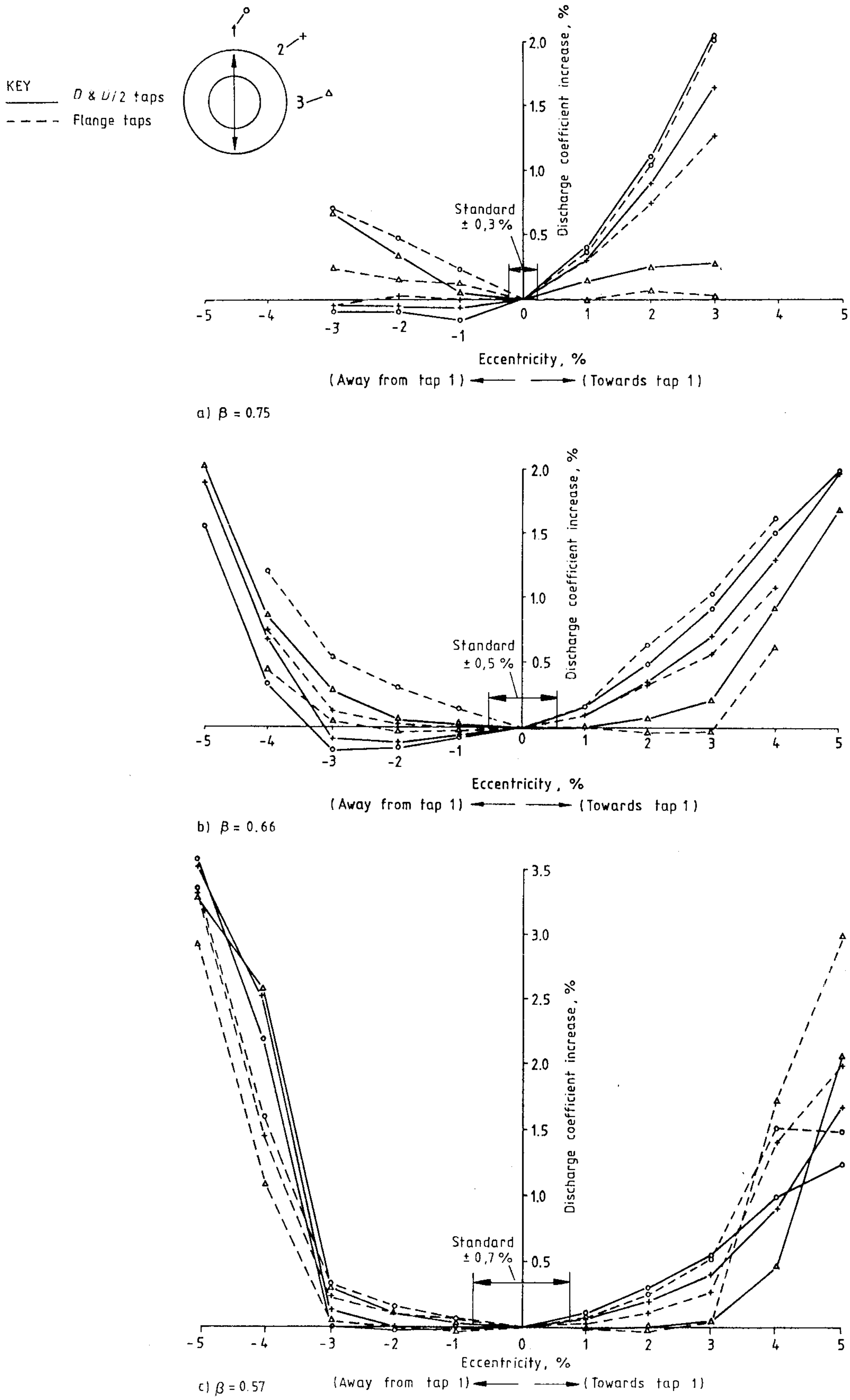


Figure 6. Discharge coefficient error vs eccentricity for an orifice plate with *D* and *D*/2 and flange taps

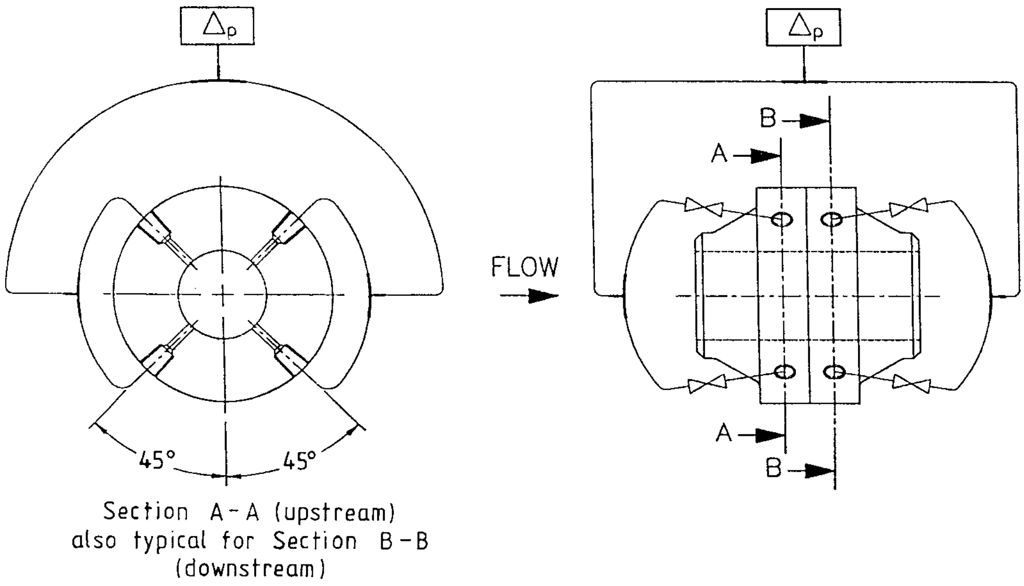


Figure 7. Triple-T arrangements

Section 4. Effects of pipe layout

4.1 General

Minimum values of the straight lengths required between the primary device and various upstream fittings are given in **7.2** of BS EN ISO 5167-1 : 1992. Minimum straight lengths are given both for zero additional uncertainty and for 0.5 % additional uncertainty in the discharge coefficient.

When the minimum requirements for even 0.5 % additional uncertainty cannot be satisfied, the user should make a correction to compensate for the change in the discharge coefficient and should also increase the percentage uncertainty in its value.

Corrections and additional uncertainties for square-edged orifice plate with corner, flange and *D* and *D*/2 tappings are given in tables 3 and 4 for a variety of upstream pipe bends and fittings, respectively.

Additional data on shifts in orifice plate disharge coefficients for a large number of upstream fittings are given in Martin C.N.B. [3]

4.2 Discharge coefficient compensation

4.2.1 Corrections

The discharge coefficient can be corrected using the data in table 3 as illustrated in the following examples:

a) percentage change in coefficient is +1.1 %, therefore the coefficient should be multiplied by 1.011;

b) percentage change in coefficient is −2.3 %, therefore the coefficient should be multiplied by 0.977.

4.2.2 Additional uncertainty

The formulae for calculating the additional percentage uncertainty in discharge coefficient are given in table 4 for each type of fitting. This is in addition to the basic uncertainty in the discharge coefficient of: 0.6 % for $\beta \leq 0.6$; β % for $0.6 < \beta \leq 0.75$. In deriving the formulae, the quantity of data, its consistency and corroboration from different sources has been taken into account. Their use is illustrated in the following examples.

a) If the equation to be applied is:

$$e = 0.5\,(1 + |c|) \qquad (7)$$

where $|c|$ is the modulus of percentage change, (i.e. the magnitude irrespective of sign) and if the change in the coefficient is + 1.4 %, then e = 1.2 %.

b) If the equation to be applied is:

$$e = 0.5 + |c| \qquad (8)$$

and if c = −2.8 %, then e = 3.3 %.

4.3 Pressure tappings

It is emphasized that the change in the coefficient when *D* and *D*/2 tappings are used is often different from those obtained with corner or flange tappings.

When the upstream straight pipe length is less than that required for zero additional uncertainty, it is recommended that multi-tappings with triple-T connections, as shown in figure 7, are used. If single tappings are used, their axes should be at right angles to the plane of the nearest upstream bend.

4.4 Devices for improving flow conditions

Flow conditioners should always be used where asymmetric or swirling flow has to be measured. Clause **7.3** of BS EN ISO 5167-1 : 1992 describes the installation position for five types of conditioners. If the conditioner cannot be installed as specified, or if the installation requirement in **7** of BS EN ISO 5167-1 : 1992 cannot be met, the use of a perforated plate should be considered. Several patented devices are available but one unpatented device is illustrated in figure 8.

These devices will result in significant reduction in flow profile asymmetry and swirl when placed at least 4 *D* after the flow disturbance ($S_{L,1} \geq 4\,D$) and at least 10 *D* before the primary device ($S_{L,2} \geq 10\,D$ in figure 9).

These distances should be increased whenever possible, and where a total straight length of more than ten pipe diameters exists upstream of the primary device it is better to increase the distance between the straightener and the plate than to increase the distance between the fitting and the straightener.

The performance of perforated plate flow conditioners varies according to the design. Plates reduce gross distortions in flow profile and hence gross errors in measured flow. Shifts in discharge coefficient should not exceed 0.2 % when the plate is correctly positioned.

Table 3. Percentage discharge coefficient changes (c) when the straight pipe lengths before the orifice are less than those specified in BS EN ISO 5167-1

Upstream straight length	β	Type of fitting (for details of nomenclature, see key)																
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
4*D*	0.5	−1.4	−1.4	−0.5	+2.9	+2.9	−0.4	+8.2		+0.2	+0.2	−1.0	−0.8	+0.3	+0.5	+0.2		
	0.6	−2.3	−2.2	−1.1	+1.7	+1.3	−1.2	+8.5		−0.2	−0.3	−2.4	−1.7	+0.3	0	−0.2		
	0.7	−3.8	−3.2	−1.8	+0.1	+0.4	−2.1	+8.2		−0.9	−0.7	−4.4	−2.3	+0.3	−0.6	0		
	0.8	−5.6	−3.9	−2.6	−2.4	+0.5	−3.1	+3.4		−2.2	−0.2	−7.5	−1.0	+0.3	−1.3	+0.8		
8*D*	0.5	1)	1)	−0.3	+2.4	+2.4	0	+6.3	+6.4	−0.2	−0.2	−0.6	−0.4	1)	−0.2	−0.2	−0.8	−0.7
	0.6	−1.4	−1.2	−0.7	+1.4	+1.2	−0.7	+5.6	+6.1	−0.6	−0.4	−1.3	−1.2	1)	−0.7	−0.8	−1.3	−1.2
	0.7	−2.2	−1.9	−1.2	+0.3	+0.4	−1.3	+4.4	+6.1	−1.1	−0.8	−2.1	−1.9	+0.1	−1.2	−1.2	−1.7	−1.7
	0.8	−3.2	−2.7	−1.8	−1.7	+0.4	−2.0	+2.3	+10.0	−1.9	−1.7	−3.1	−2.0	+0.1	−1.8	−1.0	−2.0	−2.1
12*D*	0.5	1)	1)	1)	+2.0	+2.0	0	+5.5	+5.5	−0.2	−0.1	−0.4	−0.3	1)	−0.3	−0.2		
	0.6	1)	1)	−0.4	+1.2	+1.0	−0.4	+3.9	+4.3	−0.4	−0.3	−0.9	−0.9	1)	−0.7	−0.6	−0.8	−0.8
	0.7	−1.4	−1.4	−0.8	+0.3	+0.3	−0.8	+2.6	+3.2	−0.8	−0.7	−1.3	−1.3	1)	−1.1	−1.0	−1.2	−1.1
	0.8	−2.0	−2.0	−1.3	−1.3	+0.3	−1.3	+1.5	+6.8	−1.3	−1.4	−1.7	−1.6		−1.5	−1.2	−1.5	−1.4
16*D*	0.5	1)	1)	1)	+1.7	+1.7	0	+5.1	+5.0	−0.1	0	−0.2	−0.2	1)	−0.2	−0.2		
	0.6	1)	1)	1)	+1.1	+0.9	−0.3	+3.5	+3.6	−0.3	−0.2	−0.6	−0.6	1)	−0.4	−0.4		
	0.7	1)	1)	−0.5	+0.3	+0.3	−0.5	+2.1	+2.4	−0.5	−0.5	−0.9	−1.0	1)	−0.7	−0.6	−0.9	
	0.8	−1.3	−1.3	−0.7	−1.1	+0.3	−0.8	+0.8	+5.1	−0.8	−1.1	−1.0	−1.3	1)	−1.0	−0.8	−1.2	

1) Refer to table 3 of BS EN ISO 5167-1 : 1992.

Key

Number	Type of upstream fitting	Type of taps	Number	Type of upstream fitting	Type of taps
1	Single short radius 90° bend	Corner, flange	10	Butterfly valve, fully open	*D* and *D*/2
2	Single short radius 90° bend	*D* and *D*/2	11	Butterfly valve, 52° open	Corner, flange
3	Two 90° bends in the same plane, configuration 'U' or 'S'	All	12	Butterfly valve, 52° open	*D* and *D*/2
4	Two 90° bends at right angles, no spacer	Corner, flange	13	Gate valve, fully open	All
5	Two 90° bends at right angles, no spacer	*D* and *D*/2	14	Gate valve, ⅔ open	Corner, flange
6	Two 90° bends at right angles, 5*D* to 11*D* spacer	All	15	Gate valve, ⅔ open	*D* and *D*/2
7	Two 90° mitre bends at right angles, no spacer	Corner, flange	16	Gate valve, ¼ open and globe valve	All
8	Two 90° mitre bends at right angles, no spacer	*D* and *D*/2	17	Symmetrical restriction or enlargement, tapered or abrupt	All
9	Butterfly valve, fully open	Corner, flange			

NOTE. For β greater than 0.75 the *D* and *D*/2 taps should not be used as the downstream tap is in the pressure recovery region if $L_2' > 2(1 - \beta)$

Table 4. Formulae for additional uncertainty in the orifice discharge coefficient, to be used with the percentage changes given in table 3, for all tapping arrangements

Type of upstream fitting	Additional uncertainty formulae (c is the percentage change in discharge coefficient)	
	Piezometer ring e.g. Triple-T	**Single tapping**[1)]
Single short radius 90° bend. Bend radii 1D to 1.5D	$0.5\ (1 + 0.6\ \lvert c \rvert)$	$0.5 + 0.6\ \lvert c \rvert$
Two 90° bends, U or S, in same plane	$0.5\ (1 + \lvert c \rvert)$	$0.5 + \lvert c \rvert$
Two 90° bends at right angles, no spacer (where X is the distance from the orifice plate to the nearest bend)	$0.5\ (1 + \lvert c \rvert) + \frac{10}{X/D}$	$0.5 + \lvert c \rvert + \frac{10}{X/D}$
Two 90° bends at right angles, 5D to 11D spacer	$0.5 + \lvert c \rvert$	$0.5\ (1 + 3\ \lvert c \rvert)$
Two 90° mitre bends at right angles, no spacer	$0.5 + \lvert c \rvert$	$0.5\ (1 + 3\ \lvert c \rvert)$
Butterfly valve, fully open	$0.5 + \lvert c \rvert$	$0.5\ (1 + 3\ \lvert c \rvert)$
Butterfly valve, 52° open	$0.5 + \lvert c \rvert$	$0.5\ (1 + 3\ \lvert c \rvert)$
Gate valve, fully open	$0.5\ (1 + \lvert c \rvert)$	$0.5 + \lvert c \rvert$
Gate valve, ⅔ open	$0.5\ (1 + \lvert c \rvert)$	$0.5 + \lvert c \rvert$
Gate valve, ¼ open and globe valve	$0.5 + \lvert c \rvert$	$0.5 + \lvert c \rvert$
Symmetrical restriction or enlargement, tapered or abrupt	$0.5 + \lvert c \rvert$	$0.5 + \lvert c \rvert$

[1)] The tapping axis should be at right angles to the plane of the nearest upstream bend.

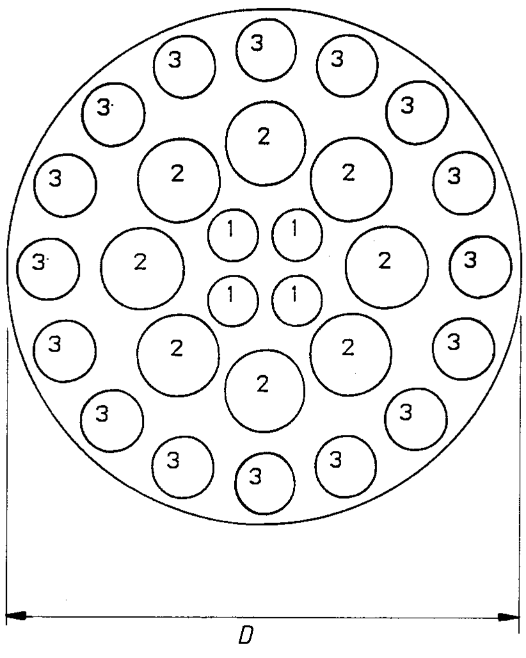


Plate thickness, $t = 0.12\ D$
Hole diameter, $d_1 = 0.10\ D$
Hole diameter, $d_2 = 0.16\ D$
Hole diameter, $d_3 = 0.12\ D$

Ring 1 at PCD 0.18 D, centred on the centre of the pattern
Ring 2 at PCD 0.48 D, centred on the centre of the pattern
Ring 3 at PCD 0.86 D, centred on the centre of the pattern

Ring 1: angle between holes is 90°
Ring 2: angle between holes is 45°
Ring 3: angle between holes is 22.5°

Figure 8. The NEL flow conditioner

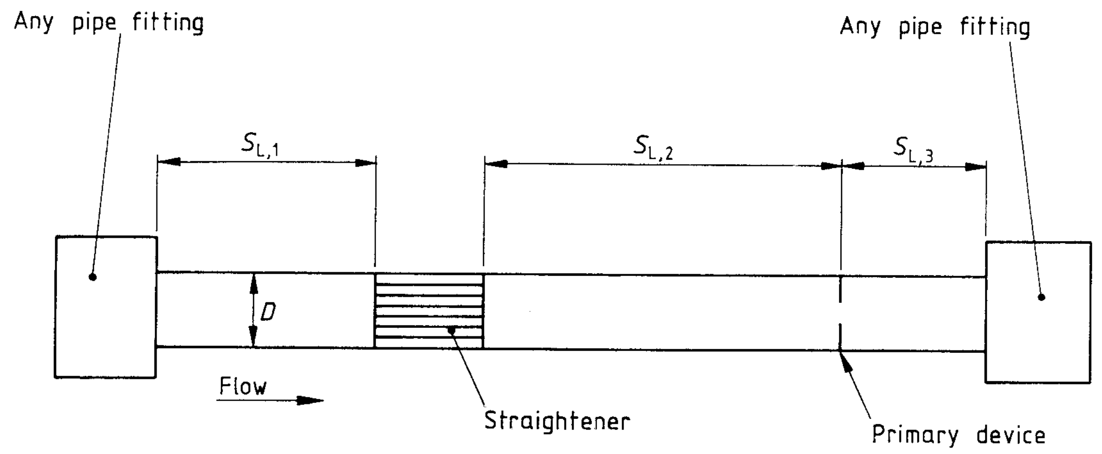


Figure 9. Flow straightener installation

Section 5. Operational deviations

5.1 General

Metering systems that conform to BS EN ISO 5167-1 when new or recently maintained may be subject to a significant degradation in accuracy over the passage of time.

This degradation may result from several causes:

a) deformation of the orifice plate;

b) deposition on the upstream face of an orifice plate;

c) deposition in the meter tube;

d) deposition and increase of surface roughness in a venturi tube;

e) rounding of the orifice plate edge;

f) deposition in the pressure tappings.

An indication of the effect of these sources of error a) to e) is given in clauses **5.2** to **5.6**.

It cannot be emphasized too strongly that the continued achievement of high accuracy requires the expenditure of considerable effort. In particular, regular inspection and maintenance are essential. Inspection periods will be dependent on the nature of the fluid being metered and on the manner of operation of the system in which the meter is installed, and can only be determined from experience.

5.2 Deformation of an orifice plate

5.2.1 General

An orifice plate may be said to be deformed when it deviates beyond the 0.5 % value specified in **8.1.2.1** of BS EN ISO 5167-1 : 1992. The deformation may be in the upstream or downstream direction, and possible causes are defects in manufacture, poor installation or incorrect use. Manufacturing and installation faults should be rectified before use.

Deformation arising from the manner of use may be either temporary (elastic) or permanent (buckling). This is discussed in Jepson and Chipchase [4], and Norman et al, 1983 [5] and 1984. [6]

5.2.2 Elastic deformation

Elastic deformation arises when the differential pressure due to flow deforms the plate by a small amount in the downstream direction, such that the induced stresses remain within the elastic limit of the plate material. For a plate simply supported at its rim, a first approximation for the percentage increase in discharge coefficient is given by:

$$c = \frac{100\ \Delta p}{Y}\left(\frac{D_2}{E}\right)^2\left(\frac{a_1\ D_2}{E} - a_2\right) \qquad (9)$$

where

$a_1 = \beta\ (0.135 - 0.155\ \beta)$

$a_2 = 1.17 - 1.06\ \beta^{1.3}$

Table 5 gives the minimum plate thickness to diameter ratio for orifice plates manufactured in AISI 304 or 316 stainless steel. This is based on $c = 0.1$ and $Y = 193 \times 10^9$ Pa

In virtually all cases, the result of the deformation is to cause an increase in the discharge coefficient.

Errors due to elastic bending may be additional to those arising from initial lack of flatness. Only when the combination of both effects results in a slope greater than 1 % under flowing conditions does the plate depart from the requirements of BS EN ISO 5167-1.

To avoid any significant increase in the overall level of uncertainty for the flow measurement, it is recommended that plate thickness and differential pressures are chosen such that the error due to elastic bending given by equation 9 is less than 0.1 %.

Since the plate will return to its undeformed state when the flow is zero, elastic bending cannot be detected during routine inspection of a metering system.

Table 5. Minimum E/D_2 ratios for orifice plate manufactured in AISI 304 or 316 stainless steel

β	Δp for maximum flowrate						
	10 kPa	30 kPa	50 kPa	75 kPa	100 kPa	200 kPa	400 kPa
0.2	0.009	0.011	0.013	0.014	0.014	0.016	0.018
0.3	0.010	0.013	0.015	0.016	0.017	0.020	0.022
0.4	0.010	0.014	0.016	0.018	0.019	0.022	0.025
0.5	0.010	0.014	0.016	0.018	0.020	0.023	0.027
0.6	0.010	0.014	0.016	0.018	0.019	0.023	0.026
0.7	0.009	0.012	0.014	0.016	0.017	0.020	0.024
0.75	0.008	0.011	0.013	0.014	0.016	0.018	0.021

5.2.3 Plastic deformation

Where an orifice plate has been subjected to excessive differential pressures it may deform permanently. When the deformation is known, the error may be estimated from figure 10. Such deformation may occur during over-rapid pressurization or venting of a line containing a compressible fluid, or through an abnormal flow condition. It should be emphasized that a permanently deformed plate should be discarded.

The differential pressure required to yield a simply supported orifice plate may be estimated from:

$$\Delta p_y = \sigma_y \left(\frac{E}{D_2}\right)^2 \left(\frac{1}{0.681 - 0.651\,\beta}\right) \qquad (10)$$

To avoid deformation it is recommended that the following procedure be used when choosing the thickness of an orifice plate:

a) a calculation should be made using equation 9 for normal operation;

b) a second calculation should be made using equation 10 selecting the anticipated value for the maximum differential pressure that might occur under fault conditions;

c) the greater thickness should be chosen within the limit of 0.05 D, as specified in **8.1.4.3** of BS EN ISO 5167-1.

Example:

a) From equation 9 with c = 0.1

β = 0.2

Y = 193 × 10^9 Pa

Δp = 5 × 10^4 Pa

gives E/D_2 > 0.013, from equation 9 or (table 5);

b) From equation 10

β = 0.2

σ_y = 300 × 10^6 Pa for stainless steel but for design purposes it is advisable to use

σ_y = 100 × 10^6 Pa (safety factor of 3)

Anticipating Δp_y = 10^5 Pa gives $E/D_2 \geq 0.023$;

c) Consequently E/D_2 should be at least 0.023.

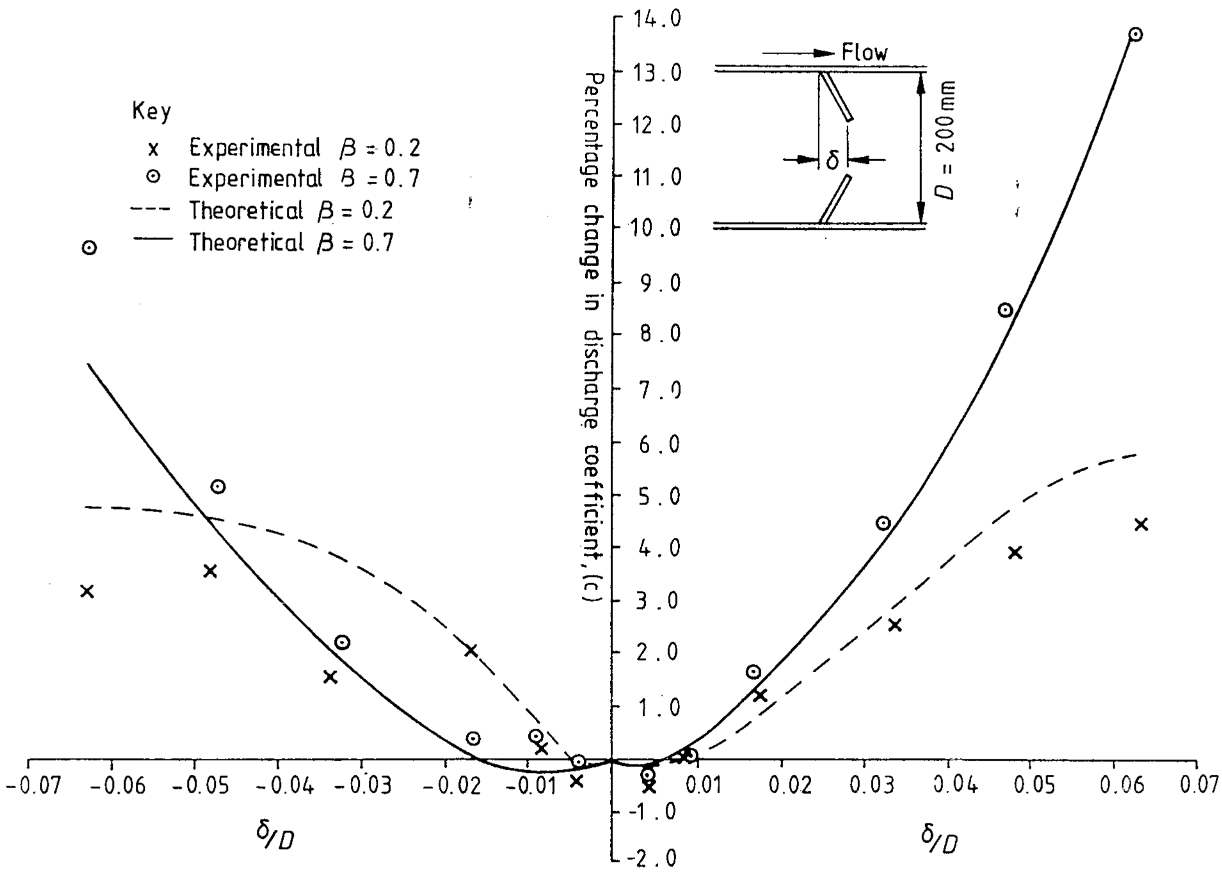


Figure 10. Effect of orifice plate deformation on flow measurement accuracy

5.3 Deposition on the upstream face of an orifice plate

The effect of deposits on the upstream face of an orifice plate is similar to that of upstream face roughness and always causes the discharge coefficient to increase.

Table 6 shows the effect of a uniform layer of sand one grain thick (grain size 0.4 mm) and the effect of grease spots (each nominally 6.3 mm diameter and 2.5 mm high) on an orifice plate in a 100 mm diameter meter tube measuring air at atmospheric pressure. Table 6 shows the importance of the annular region around the entrance to the orifice bore. As this region is usually scrubbed by the flow, the actual errors are probably smaller than those indicated.

5.4 Deposition in the meter tube

In an exercise to simulate the effect of deposition in the meter tube, welding rods were stacked axially against the upstream face of an orifice plate as shown in figure 11. The rods caused an increase in the discharge coefficient.

Figure 12 shows the results of tests carried out to investigate the effect of a smooth horizontal build up of material in a meter run. When the material is below the dam height, the discharge coefficient increases. When the build up exceeds the dam height, the orifice bore cross-sectional area is reduced, leading to a decrease in discharge coefficient.

5.5 Deposition and increase of surface roughness in Venturi tubes

5.5.1 General

Two effects may occur in a Venturi tube which has been in use for a period of time. These are deposition of material in the contraction and the bore, and an increase in the surface roughness. Both effects result in a decrease in the discharge coefficient and both effects may occur together. They are, however, considered separately in **5.5.2** and **5.5.3**.

5.5.2 Deposition

If material is deposited smoothly and uniformly in the contraction and bore of a Venturi tube, the change in discharge coefficient, expressed as a percentage, may be estimated theoretically from the reduction in area as:

$$c = -400\left(\frac{x}{d}\right) \qquad (11)$$

where x is the thickness of the annular deposit in the bore of the Venturi tube (in m).

5.5.3 Surface roughness

The chemical nature of the fluid and the material of the Venturi tube may be such that the surface roughness of the Venturi tube increases with time (Hutton [7]). This increase in roughness leads to a reduction in the discharge coefficient. An indication of the error involved is given in figure 13.

The rate of increase of surface roughness is dependent on the chemical reactions occurring in the metering system, and is outside the scope of this standard.

5.6 Orifice plate edge sharpness

5.6.1 Deterioration

The sharp edge of an orifice plate may deteriorate with time. Possible causes of this deterioration are:

a) erosion;

b) cavitation;

c) mechanical damage;

d) careless handling.

Orifice plate discharge coefficients are sensitive to edge sharpness and where any of the above effects may occur, regular quantitative inspection of the edge should be made.

The effect of loss of sharp edge is described in **2.1**.

5.6.2 Plate reversal

Particular care should be taken to ensure that bevelled orifice plates are inserted into the meter line with the bevel on the downstream face.

In a 100 mm diameter meter, a plate bevelled at 45° and facing upstream can give the following percentage increase in discharge coefficient:

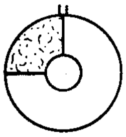
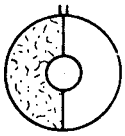
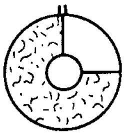
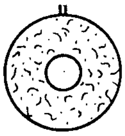
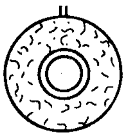
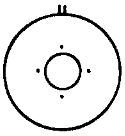
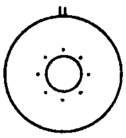
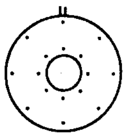
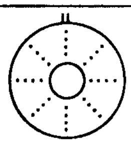
a) 0.25 mm bevel width: $c = 2.0$;

b) 0.5 mm bevel width: $c = 4.0$;

c) 1.25 mm bevel width: $c = 13.0$.

These values should be taken simply as indicative of changes which can occur by incorrect installation and should not be taken as precise.

Table 6. Effect of deposits on β = 0.2 and β = 0.7 orifice plates

Type of deposit			Change in discharge coefficient	
			β = 0.2	β = 0.7
Sand		1 sand quadrant	% +1.0	% +0.8
		2 sand quadrants	+2.8	+1.9
		3 sand quadrants	+3.9	+2.4
		4 sand quadrants	+6.2	+3.0
		4 sand quadrants with 6 mm ring removed from around orifice bore	+0.3	+0.3
Grease		4 grease deposits	+1.0	+0.1
		8 grease deposits	+2.8	+1.3
		16 grease deposits	+2.1	+1.2
		32 grease deposits	+2.6	+0.6

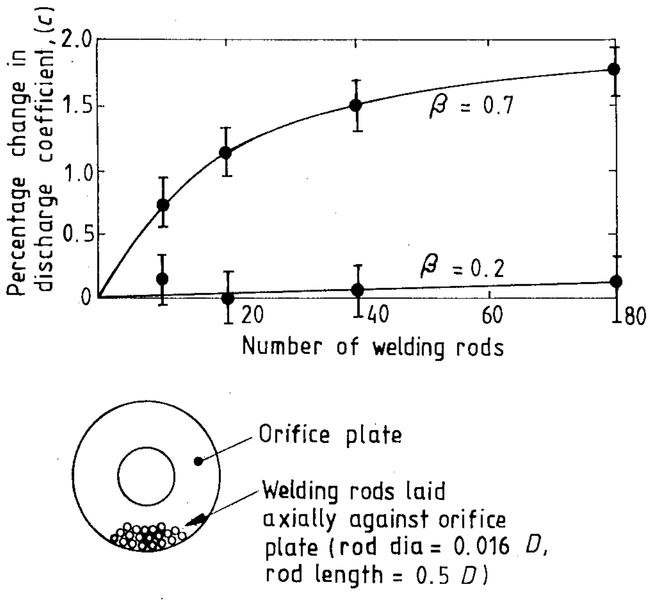


Figure 11. Effect of welding rods in meter tube

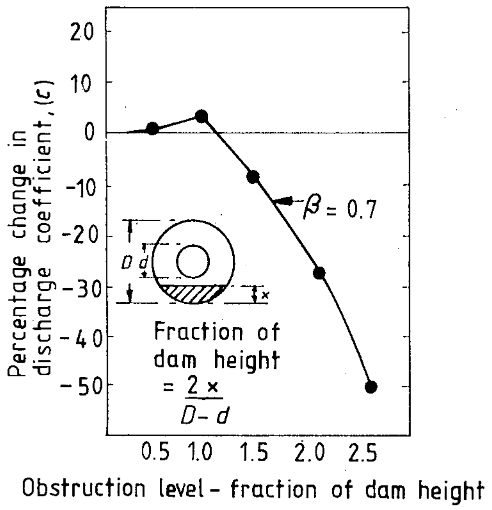


Figure 12. Effect of debris in meter tube (on both sides of plate)

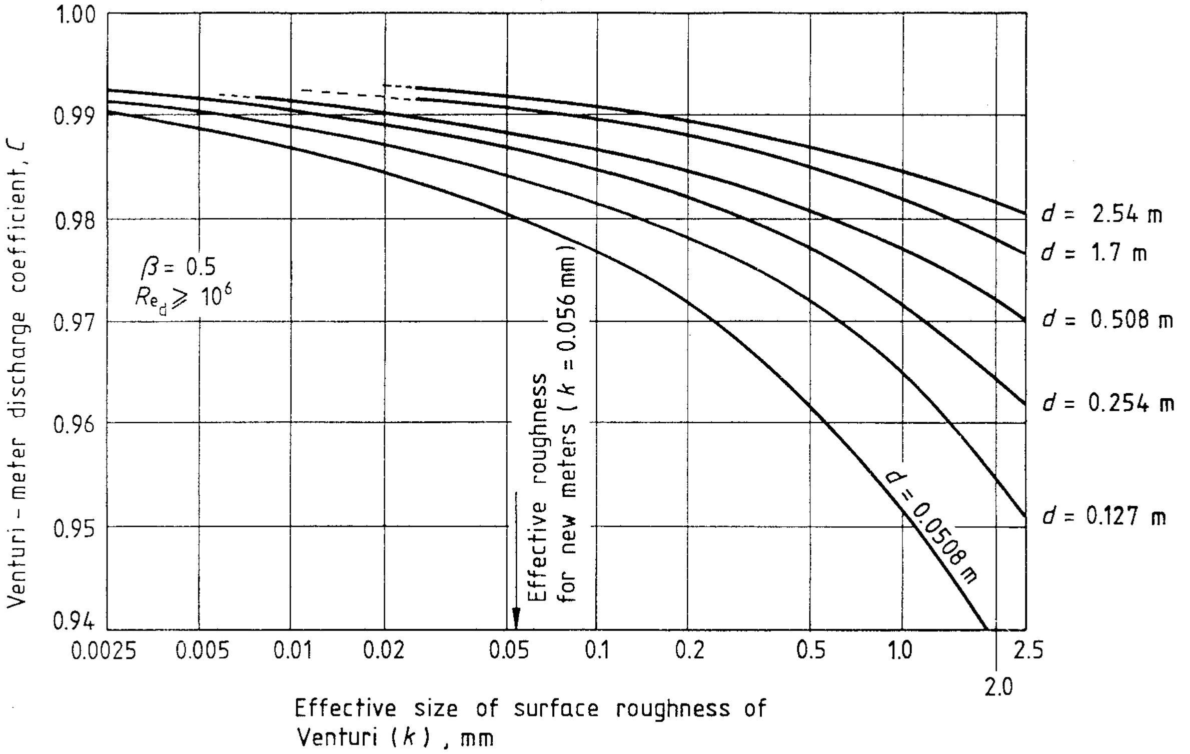


Figure 13. Variation of Venturi meter coefficient with surface roughness

Section 6. Pipe roughness

6.1 General

The relationship between flow rate and pressure difference given in clause **3** of BS EN ISO 5167-1 : 1992 assumes conformity to specified installation conditions. In particular, the flow conditions immediately upstream of a plate should approach those of a fully developed profile.

The pipe roughness, k, Reynolds number, Re_D, and friction factor, λ, are interrelated and determine the velocity profile (see Schlichting) [8]. Experimental results suggest that the velocity profile can be described approximately by:

$$\frac{u}{u_{CL}} = (y/R)^{1/n} \qquad (12)$$

u = Local velocity at y from pipe wall

u_{CL} = Velocity at centre line ($y/R = 1$)

R = Pipe radius ($D/2$)

n = Power (dependent on Re_D and k/D)

y = Distance from pipe wall

Then the mean velocity U is given by:

$$\frac{U}{u_{CL}} = \frac{2n^2}{(n+1)(2n+1)} \qquad (13)$$

In smooth pipe n increases with Reynolds number (see table 7). In fully rough pipe n decreases with increasing relative roughness (see table 8).

Table 7. Values of n, U/u_{CL} and λ for smooth pipe

Re_D	n	U/u_{CL}	λ
4×10^3	6.0	0.791	0.04
2.3×10^4	6.6	0.807	0.025
1.1×10^5	7.0	0.817	0.0175
1.1×10^6	8.8	0.850	0.0115
2×10^6	10	0.866	0.0105

Table 8. Values of n, U/u_{CL} and λ for rough pipe

R/k	k/D	n	U/u_{CL}	λ
507	0.986×10^{-3}	6	0.791	0.020
126	3.97×10^{-3}	5	0.758	0.028
31	16.1×10^{-3}	4	0.711	0.045

A more uniform profile ($U/u_{CL} \rightarrow 1$) reduces the discharge coefficient and a more peaked profile (U/u_{CL} decreasing) increases C.

The extent to which the coefficient varies is also influenced by β, being less for smaller β.

6.2 Upstream pipe

For an orifice plate the change in discharge coefficient due to pipe roughness, ΔC, is approximately proportional both to the change in friction factor, $\Delta\lambda$, and to $\beta^{3.5}$. The friction factor, λ, can be measured directly, using:

$$\Delta p = \frac{\lambda \rho U^2 Z}{2D} \qquad (14)$$

where Δp is the difference in pressure between two tappings spaced a distance Z apart in a pipe of diameter D.

It is simpler to measure the arithmetic mean deviation of the roughness profile, R_a, to deduce the uniform equivalent roughness, k, by taking it to be approximately equal to πR_a, and to calculate λ using the Colebrook-White equation:

$$\frac{1}{\sqrt{\lambda}} = 1.74 - 2\log\left(\frac{2k}{D} + \frac{18.7}{Re_D\sqrt{\lambda}}\right) \qquad (15)$$

If it is desired to estimate the change in discharge coefficient from the discharge coefficient equation given in **8.3.2.1** of BS EN ISO 5167-1 : 1992, it is also necessary to estimate the friction factor for the discharge coefficient equation. This has to be done on the basis of the measured roughness or friction factor of the pipes in which the standard data (to which the equation was fitted) were collected.

Figure 14 gives measured and computed (using computational fluid dynamics) values of ΔC as a function of $\beta^{3.5}\Delta\lambda$ (see Reader-Harris (1990 [9]) for complete references). The computed values and the European experimental data were obtained using corner tappings. The North American experimental data (Bean et al, [15] Brennan et al [16] and Studzinski et al [17]) were obtained using flange tappings. For corner tappings, the following approximate equation has been plotted:

$$\Delta C = 3.5\beta^{3.5}\Delta\lambda \qquad (16)$$

From computational work, the effect of roughness on discharge coefficients using D and $D/2$ tappings has been found to be about 25 % less than its effect on those using corner tappings. ΔC using flange tappings lies between ΔC using corner tappings and ΔC using D and $D/2$ tappings.

In extreme cases roughness can change the diameter of the pipe and consequently β. The following information (Clark and Stephens) [9] is for such an extreme case.

Figure 15 relates to orifice plates with corner tappings and gives the discharge coefficient change for pipes with a roughness corresponding to surfaces encrusted with closely spaced spherical nodules. These averaged 6.3 mm in diameter reducing the effective diameter of the pipe by at least 6.3 mm. The changes shown would be applied to the flow using the larger clean pipe diameter. (The dotted curve for $\beta = 0.71$ applies to a sanded surface (0.5 mm to 1.0 mm diameter particles).)

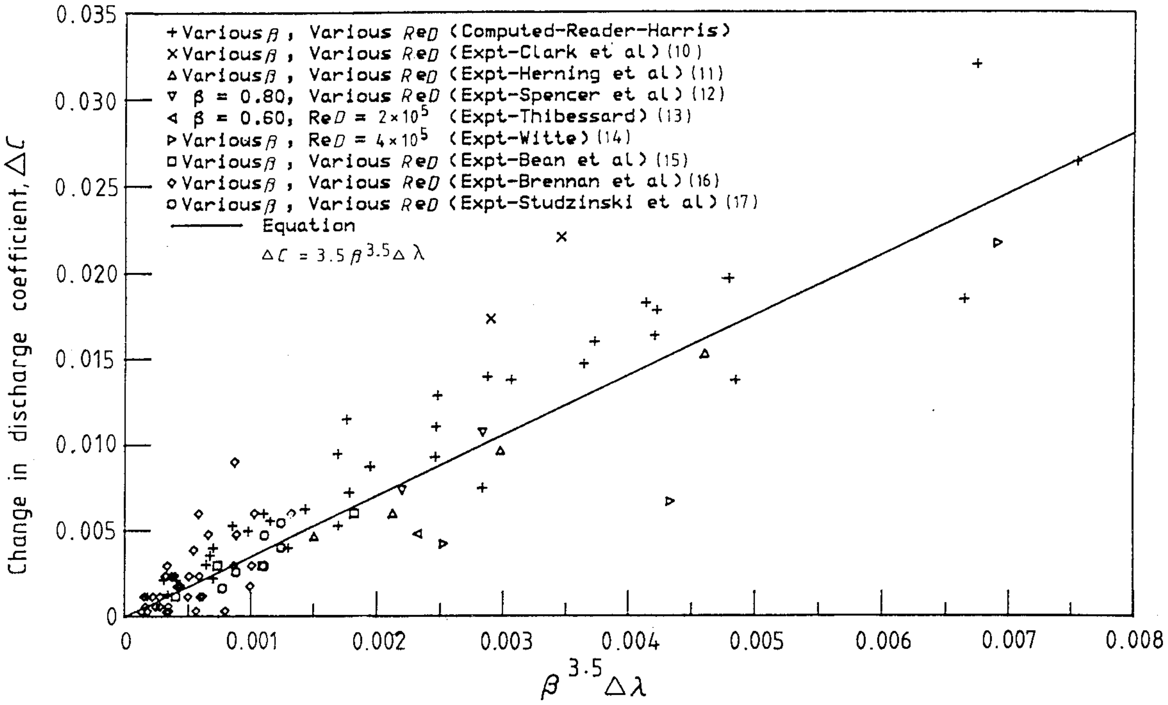


Figure 14. The effect of rough pipe on discharge coefficient

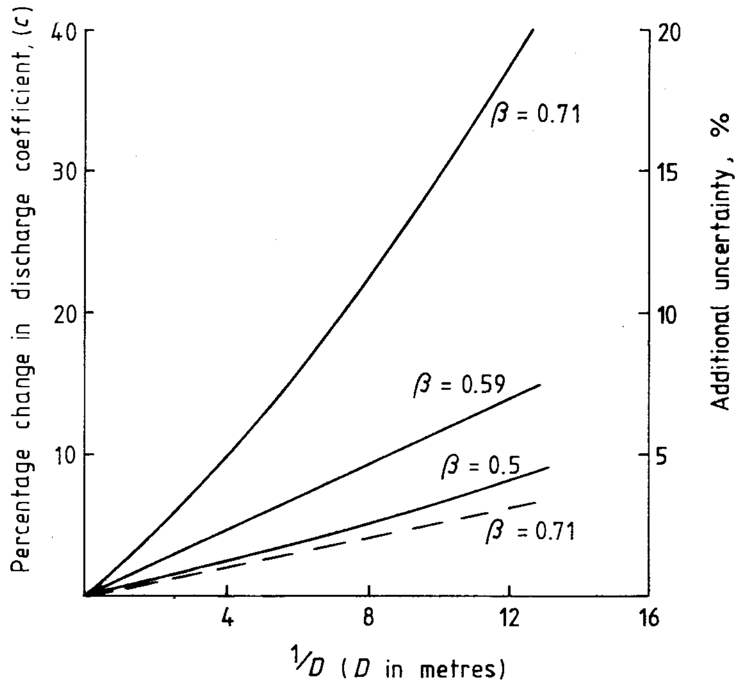


Figure 15. The combined effect of abnormal roughness and diminution in pipe bore

Figure 16 shows the coefficient changes based on similar pipe conditions to those above but calculated on the smaller effective pipe diameter D_e (= $D - 6.3$ mm) and β_e where $\beta_e = d/D_e$. The changes due to sand particles of about 1 mm diameter are about one-third of those given in figure 15.

If a measurement of the flow needs to be made under such adverse conditions, the corrected discharge coefficients given above should be used with an additional uncertainty of half the percentage discharge coefficient change.

6.3 Downstream pipe

Even severe encrustation adjacent to the downstream side of an orifice plate has no significant effect on the discharge coefficient.

6.4 Reduction of roughness effects

Experiments have shown that if a relatively short upstream length of pipe adjacent to the orifice plate is cleaned to remove the encrustations, the error is significantly reduced. Table 9 gives recommendations regarding the extent of such cleaning for various pipe sizes, values of β and types of roughness. For pipes greater than 300 mm internal diameter, fewer diameters of clean upstream pipe may be necessary.

6.5 Maintenance

In all cases of flow measurement by differential pressure meters, a cleaning routine for the pipe, the primary device and the pressure tappings should be established to suit the particular conditions. Where reasonable accuracy is required in the measurement of the flow of dirty fluids, installations should be designed for easy cleaning of the upstream pipe to an extent shown in table 9.

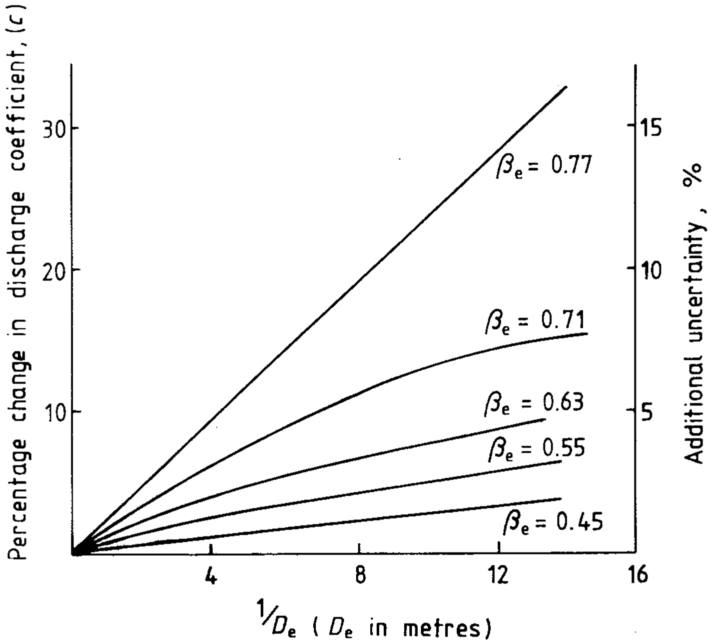


Figure 16. The effect of abnormal roughness on orifice plates

Table 9. Recommendations regarding the extent of cleaning

Pipe size (i.d.) mm	β	Type of roughness	Approximate change in discharge coefficient without cleaning the pipe	Amount of cleaning (in multiples of D) to obtain roughness errors not exceeding:				
				± 3 %	± 2 %	± 1 %	± 0.5 %	Nil
76	0.5 to 0.59 0.71 0.71	7.0 mm spheres 7.0 mm spheres Sand	9 - 15 % 40 % 7 %	3 to 4 4 to 10	4 to 5 10 to 20 3 to 5	5 to 15 20 to 25 5 to 25	15 to 20 25 to 30 25 to 30	> 20 > 30 > 30
152	0.5 to 0.59 0.71 0.71	7.0 mm spheres 7.0 mm spheres Sand	4 - 8 % 17 % 4 %	2.5 to 4	3 to 5 4 to 15 1 to 3	5 to 12 15 to 25 3 to 4	12 to 20 25 to 30 4 to 20	> 20 > 30 > 20
305	0.71 0.71	7.0 mm spheres Sand	8 % 2 %		2½ to 4	4 to 6 1 to 3	6 to 15 3 to 5	> 15 > 5

Annexes

Annex A
Bibliography

Akashi, K., Watanabe, H. and Koga, K. Development of a new rectifier for shortening upstream pipe length of flow meter. In *proc*, *Imeko Symposium on Flow Measurement and Control in Industry*, pp 279-280, Tokyo, Japan, 1979.

Bean, H.S. Indications of an orifice meter. *American Gas Association Monthly*, July-August 1947, 337-341, 349.

Beitler, S.R. The flow of fluids through orifices in 6 inch pipelines. *Trans. ASME*, 1929, **52**, 751.

Blake, K.A. The design of piezometer rings. *J. Fluid Mechanics*, Nov. 1979, **78**(2), 415-428.

Brain, T.J.S and Reid, J. Measurement of orifice plate edge sharpness. *J. Inst. Measurement and Control*, Sep. 1973, **6**, 377-384.

Clark, W.J. *Flow measurement by square edged orifice plate using corner tappings*, Pergamon, 1965.

Dall, H.E. The effect of roughness of the orifice plate on the discharge coefficient. *Instrument Engineer*, April 1958, **2**(5), 91-92.

Gallagher, J. E. and La Nasa, P. J. Field performance of the Gallagher flow conditioner. In *Proc. 3rd International Conference on Fluid Flow Measurement.* San Antonio, Texas, 1995.

Gallagher, J. E., La Nasa, P. J., and Beaty, R. E. The Gallagher flow conditioner. In *Proc. North Sea Flow Measurement Workshop*, Peebles, Scotland, 1994. National Engineering Laboratory (NEL) East Kilbride, Glasgow.

Herning, F. and Wolowski, E. The edge sharpness of standard and segment orifices and the laws of similarity (in German), *Brennstoff-Wärme — Kraft*, 1963, **15**(1), 26-30.

Irving, S.J. *Effect of system layout of the discharge coefficients of orifice plates.* Parts II and III. 1977 and 1978 BHRA Reports RR 1424 and RR 1462.

Jenner, S.R. *An investigation of the influence of upstream fittings on the accuracy of flow measurement using orifice plates.* Hatfield Polytechnic, 1977. B.Sc. (Eng.) Project Report.

Jepson, P. and Chamberlain, D. Operating high pressure orifice metering installations. *Flow-Con 77. Proc. Symp. The application of flow measuring techniques.* Brighton, UK, April, 1977.

Kretzschmer, Fr. and Walzholz, G. Experiments on installation faults of standard orifice plates. *Forschung*, Jan. — Feb. 1934, **5**(1), 25 – 35. English translation available from NEL, (NEL-TT-2843).

Lake, W. T., and Reid, J. Optimal flow conditioner. In *Proc. North Sea Flow Measurement Workshop*, Peebles, Scotland, ppr 1.3, 1992. East Kilbride, Glasgow: NEL.

Laws, E.M. Flow conditioning — a new development. *Flow measurement and Instrumentation*, I. 167-170, 1990.

Laws, E. M. and Ouazzane, A. K. Flow conditioning for orifice plate flow meters. In *Proc. 3rd International Conference on Fluid Flow Measurement* San Antonio, Texas, 1995.

McVeigh, J.C. Further investigations into the effect of roughness of the orifice plate on the discharge coefficient. *Instrument Engineer*, April 1962, **3**(5), 112-113.

Mason, D. and Wilson, M.P.Jr. *Measurement error due to the bending of orifice plates*, 1975, ASME paper No. 75-WA/FM-6.

Miller, R.W. and Kneisel, O. Experimental study of the effects of orifice plate eccentricity on flow coefficients. *J. of Basic Eng.* Trans. ASME, March 1969, Series D, **91**(1), 121-131.

Nagashio, K. and Komiya, K. *Effect of upstream straight length on orifice flowmeters*. Japan, 1972. Report of the National Research Laboratory of Metrology, 21-1. English translation available from NEL.

Nagel, P. and Jaumotte, A. Influence of disturbances on the coefficients of a standardized orifice plate. *Promoclim A, Applications Thermique et Aeraulique*, 1976, **7**(1), 57-84. (in French).

Orsi, E. Influence of special parts on the operation of standardized diaphragms. *L'Energica Elettrica* NI, Italy, 1978 English translation available from NEL, (NEL-TT-2834).

Reader-Harris, M. J. The effect of pipe roughness on orifice plate discharge coefficients. Progress Report No PR9: EUEC/17 (EEC005). East Kilbride, Glasgow: National Engineering Laboratory, 1990. Available on microfiche as Report EUR 13763, Commission of the European Communities, Brussels, Belgium, 1991.

Reader-Harris, M. J. Computation of flow through orifice plates. *Numerical Methods in Laminar and Turbulent Flow*, Volume 6, C Taylor, P Gresho, R. L. Sani and J Haüser (eds) (*Proc. 6th Int. Conf. on Numerical Methods in Laminar and Turbulent Flow, Swansea*), Part 2, pp 1907-1917. Swansea: Pineridge Press, 1989.

Reader-Harris, M. J., Sattary, J. A. and Spearman, E. P. *The orifice discharge coefficient equation.* Progress Report No PR14: EUEC/17 (EEC005). East Kilbride, Glasgow: National Engineering Laboratory Executive Agency, 1992.

Reader-Harris, M. J., Sattary, J. A. and Woodhead, E. The use of flow conditioners to improve flow measurement accuracy downstream of headers. In *Proc. 3rd International Conference on Fluid Flow Measurement*, San Antonio, Texas, 1995.

Roark and Young. *Formulas for stress and strain*, 5th ed., McGraw Hill, 1975.

West. R.G. Developments in flow metering by means of orifice plates. Paper B-3 in: *Flow measurement in closed conduits*. Edinburgh, HMSO, 1962.

Wilcox, P. L., Weberg, T. and Erdal, A. Short gas metering systems using K-Lab flow conditioners. *In Proc. North Sea Flow Measurement Workshop* 1990

List of references

Normative references

BSI publications

BRITISH STANDARDS INSTITUTION, London

BS 1042	*Measurement of fluid flow in closed conduits*
BS 1042 : Section 2.1 : 1998	*Method using Pitot static tubes*
BS EN ISO 5167-1 : 1992	*Specification for square-edged orifice plates, nozzles and venturi tubes inserted in circular cross-section conduits running full*

Informative references

Other references

[1] Hobbs, J.M. and Humphreys, J.S. The effect of orifice plate geometry upon discharge coefficient. *Flow measurement and instrumentation*, Volume 1, No 3, April 1990.

[2] Husain Z.D. and Teyssandier R.G. The effects of plate thickness and bevel angle in a 150 mm line size orifice meter — *Pro international conference in the mid 80's*. June '86 N.E.L.

[3] Martin, C.N.B. Effects of upstream bends and valves on orifice plate pressure distributions and discharge coefficients. N.E.L. Report 702, 1982.

[4] Jepson, P. and Chipchase, R. The effect of plate buckling on orifice meter accuracy. *JMES*, 1975, **17**(6).

[5] Norman, R., Rawat, M.S. and Jepson, P. Buckling and eccentricity effects on orifice metering accuracy, *Proc. 1983 International Gas Research Conference*. London, UK, 13-16 June 1983.

[6] Norman, R., Rawat, M.S. and Jepson, P. An experimental investigation into the effects of plate eccentricity and elastic deformation on orifice meter accuracy. *Proc. International Conference on the Metering of Natural Gas and Liquefied Hydrocarbon Gases*. London, UK, February 1984.

[7] Hutton, S. P. The prediction of Venturi meter coefficients and their variation with roughness and age. 3 (III), *Proc. Inst. Civil Eng.* April 1954, 216, 241, 922-927.

[8] Schlichting, H. Boundary layer theory. McGraw-Hill New York, 1960.

[9] Reader-Harris, M. J. Pipe roughness and Reynolds number limits for the orifice plate discharge coefficient equation. *Proc. 2nd Int. Symp. on Fluid Flow Measurement*, Calgary, Canada, 6-9 June 1990, pp 29-43. Arlington, Virginia: American Gas Association, 1990.

[10] Clark, W.J. and Stephens, R.C. Flow measurement by square edged orifice plates: pipe roughness effects. *Inst. Mech. Engineering*, 1957, 171(33), 895-904.

[11] Herning, Fr. and Lugt, H. Neue Versuche mit Segmentblenden und Normblenden. *Brennst-Wärme-Kraft*,1958, **10**(5), 219-223.

[12] Spencer, E. A., Calame, H. and Singer, J. *Edge sharpness and pipe roughness effects on orifice plate discharge coefficients*. NEL Report No 427, East Kilbride, Glasgow: National Engineering Laboratory, 1969.

[13] Thibessard, G. Le coefficient de débit des diaphragmes, la rugosité et le nombre de Reynolds. *Chaleur et Industrie*, 1960, 415, 33-50.

[14] Witte, R. Neue Beiträge zur internationalen Normung auf dem Gebiete der Durchflußmessung. *Brennst-Wärme-Kraft*, 1953, **5**(6), 185-190.

[15] Bean, H.S. and Murdock, J. W. *Effects of pipe roughness on orifice meter accuracy, Report of Supervising Committee on two-inch tests*. American Gas Association Research Project NW-20, American Gas Association, New York, NY, 1959.

[16] Brennan, J. A., McFaddin, S. E., Sindt, C. F. and Wilson, R. R. *Effect of pipe roughness on orifice flow measurement*. NIST Technical Note 1329. Boulder, Colorado: National Institute of Standards and Technology, 1989.

[17] Studzinski, W., Berg, D., Bell, D. and Karwacki, L. Effect of meter run roughness on orifice meter accuracy. *Proc. 2nd Int. Symp. on Fluid Flow Measurement*, pp 1-15, Calgary, Canada, 1990.

BSI — British Standards Institution

BSI is the independent national body responsible for preparing British Standards. It presents the UK view on standards in Europe and at the international level. It is incorporated by Royal Charter.

Revisions

British Standards are updated by amendment or revision. Users of British Standards should make sure that they possess the latest amendments or editions.

It is the constant aim of BSI to improve the quality of our products and services. We would be grateful if anyone finding an inaccuracy or ambiguity while using this British Standard would inform the Secretary of the technical committee responsible, the identity of which can be found on the inside front cover. Tel: 020 8996 9000. Fax: 020 8996 7400.

BSI offers members an individual updating service called PLUS which ensures that subscribers automatically receive the latest editions of standards.

Buying standards

Orders for all BSI, international and foreign standards publications should be addressed to Customer Services. Tel: 020 8996 9001. Fax: 020 8996 7001.

In response to orders for international standards, it is BSI policy to supply the BSI implementation of those that have been published as British Standards, unless otherwise requested.

Information on standards

BSI provides a wide range of information on national, European and international standards through its Library and its Technical Help to Exporters Service. Various BSI electronic information services are also available which give details on all its products and services. Contact the Information Centre. Tel: 020 8996 7111. Fax: 020 8996 7048.

Subscribing members of BSI are kept up to date with standards developments and receive substantial discounts on the purchase price of standards. For details of these and other benefits contact Membership Administration. Tel: 020 8996 7002. Fax: 020 8996 7001.

Copyright

BSI
389 Chiswick High Road
London
W4 4AL