TECHNICAL REPORT

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Measurement of fluid flow by means of pressure-differential devices — Guidelines to the effect of departure from the specifications and operating conditions given in ISO 5167-1

Mesurage du débit des fluides au moyen d'appareils déprimogènes — Lignes directrices relatives aux effets de divergence par rapport aux spécifications et conditions de fonctionnement données dans l'ISO 5167-1

Contents

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The main task of technical committees is to prepare International Standards. In exceptional circumstances a technical committee may propose the publication of a Technical Report of one of the following types:

— type 1, when the required support cannot be obtained for the publication of an International Standard, despite repeated efforts;

— type 2, when the subject is still under technical development or where for any other reason there is the future but not immediate possibility of an agreement on an International Standard;

— type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example).

Technical Reports of types 1 and 2 are subject to review within three years of publication, to decide whether they can be transformed into International Standards. Technical Reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

ISO/TR 12767, which is a Technical Report of type 3, was prepared by Technical Committee ISO/TC 30, *Measurement of fluid flow in closed conduits*, Subcommittee SC 2, *Pressure-differential devices.*

Annex A of this Technical Report is for information only.

Introduction

ISO 5167-1 is an International 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 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 ISO 5167-1, and it is presented in this Technical Report as a guideline to users of flow-metering equipment.

Measurement of fluid flow by means of pressure-differential devices — Guidelines to the effect of departure from the specifications and operating conditions given in ISO 5167-1

1 Scope

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

It should not be inferred that additional tolerances or corrections can necessarily compensate for the effects of deviating from ISO 5167-1. 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 Technical Report 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 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 Technical Report.

2 Reference

ISO 5167-1:1991, *Measurement of fluid flow by means of pressure-differential devices — Part 1: Orifice plates, nozzles and Venturi tubes inserted in circular cross-section conduits running full*.

3 Symbols and definitions

3.1 Symbols

For the purposes of this Technical Report, the symbols given in Table 1 apply.

3.2 Definitions

For the purposes of this Technical Report, the definitions given in ISO 5167-1 and the following definitions apply.

3.2.1
square edge
angular relationship between the orifice bore of the flow measurement device and the upstream face, when the angle between them is 90° ± 0,3°

3.2.2
sharpness
radius of the edge between the orifice bore of the flow measurement device 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 $\left(\equiv 100\ \dfrac{\Delta C}{C} \right)$	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}	Centreline 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

4 Effect of errors on flowrate calculations

4.1 General

In this Technical Report the effects of deviations from the conditions specified in 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:

$$C = \frac{4 \, q_m \, \sqrt{(1 - \beta^4)}}{\varepsilon_1 \, \pi \, d^2 \, \sqrt{(2\Delta p \, \rho_1)}} \tag{1}$$

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_c, as

$$\frac{flow \ area}{geometric \ area} \, ,$$

the orifice produces $C_c \cong 0,6$, which mainly accounts for the discharge coefficient, $C \cong 0,6$.

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.

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.

5 Effects of deviations in construction

5.1 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 ISO 5167-1 : 1991), 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.
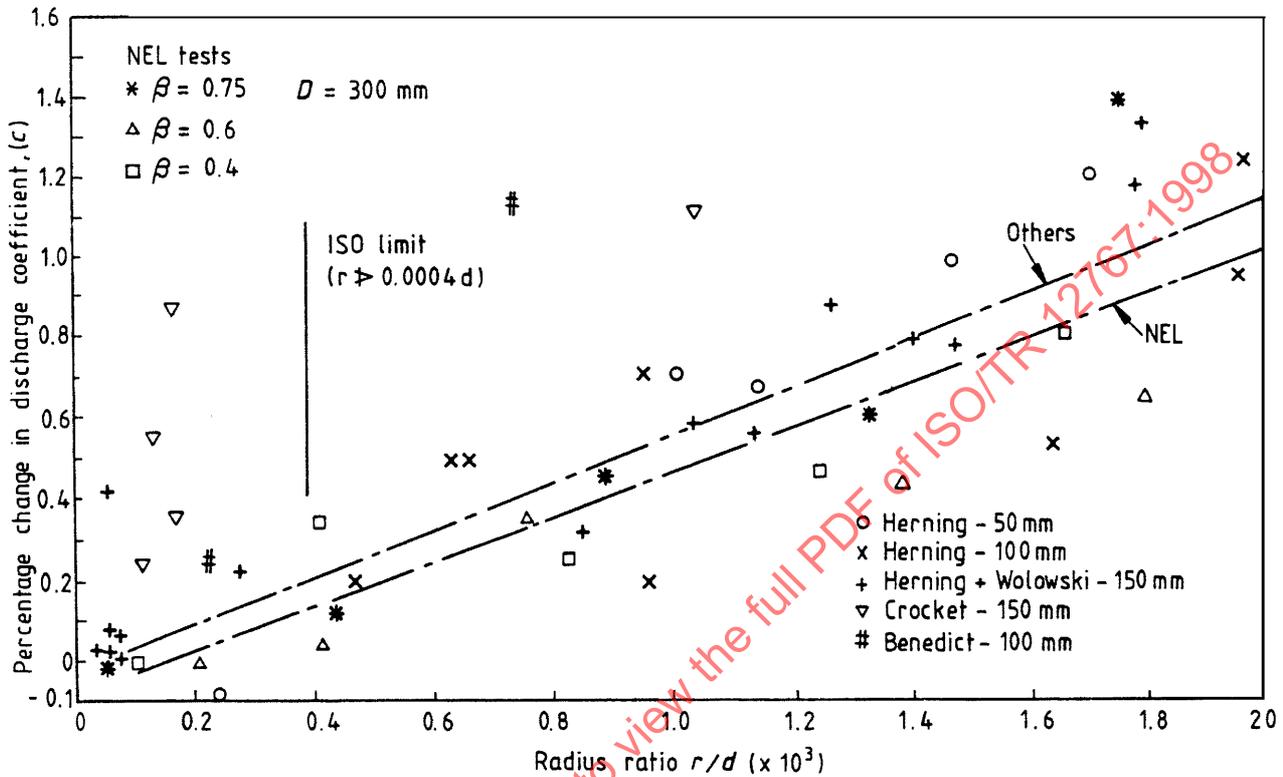

Figure 1 — Effect of edge radius on discharge coefficient

5.2 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 ISO 5167-1 : 1991) 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]).

5.3 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.
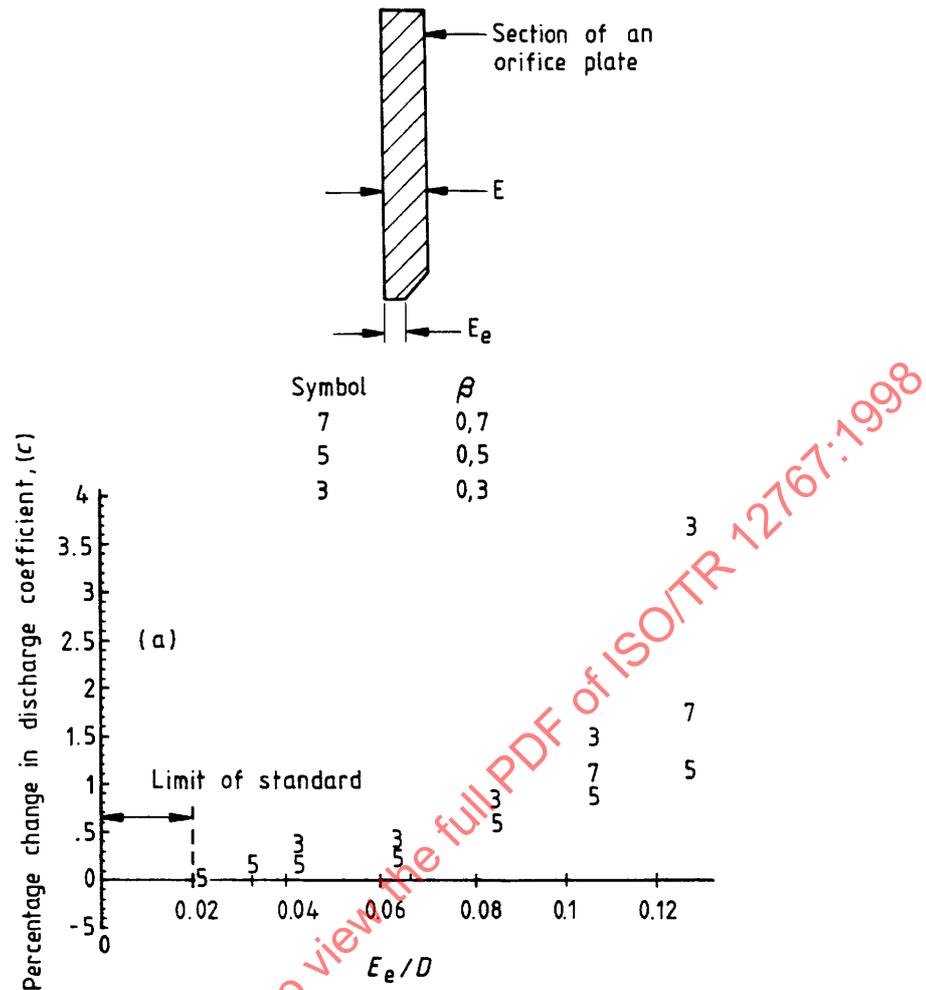
Figure 2 — Change in discharge coefficient as a function of orifice thickness

5.4 Position of pressure meter tappings for an orifice

5.4.1 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 ISO 5167-1 : 1991). Where the tapping positions fall outside the tolerances permitted in ISO 5167-1 for the three positions, the discharge coefficient may be estimated as described in 5.4.2. It should be emphasized that an additional uncertainty factor needs to be associated with the use of non-standard tapping positions.

5.4.2 Calculation of discharge coefficient

Calculate the actual values of L_1 and L'_2. The discharge coefficient can be estimated only if $L_1 \leq 1$ and $L'_2 \leq 0,47$.

Using the actual values of L_1 and L'_2, estimate the discharge coefficient using the Stolz equation.

5.4.3 Estimation of additional uncertainty

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

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

5

where

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

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

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

$$e = 25 \left| \frac{C_{D\&D/2}}{C_{FL}} - 1 \right| \tag{3}$$

where

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

5.4.4 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 A.8 and A.2 respectively of ISO 5167-1 : 1991:

C_{FL} = 0,6049

$C_{D\&D/2}$ = 0,6067

Therefore, additional uncertainty = $25 \left| \dfrac{0,6067}{0,6049} - 1 \right|$ % $\tag{4}$

= 0,074 %

The uncertainty of the discharge coefficient is 0,6 % (see 8.3.3.1 of ISO 5167-1 : 1991);

Therefore, overall uncertainty = $0,6 + 0,074 \approx 0,7$ % (i.e. the uncertainty has been simply added arithmetically).

5.5 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.

6 Effects of pipeline near the meter

6.1 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 ISO 5167-1 : 1991. Errors in the upstream internal diameter measurement will cause errors in the calculated rate of flow, which are given by:

$$\frac{\delta q_{\mathrm{m}}}{q_{\mathrm{m}}} = \frac{-2\ \beta^4}{(1 - \beta^4)} \cdot \frac{\delta D}{D} \tag{5}$$

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 ISO 5167-1 : 1991).

6.2 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 %.

6.3 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 ISO 5167-1 : 1991. 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.
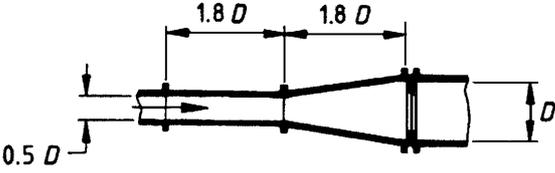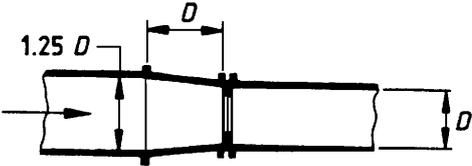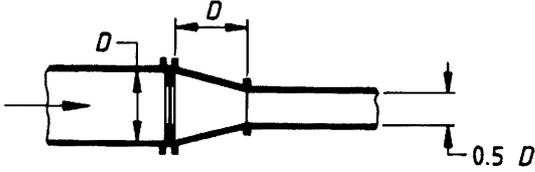
6.4 Undersize joint rings

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.

6.5 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 ISO 5167-1 : 1991 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 $\pm 30°$ 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	+ 10
	0,7	+ 50
b) Immediately downstream from a convergent taper piece	0,4	− 0,5
	0,7	− 2
c) Immediately upstream from a convergent taper piece	0,4	0 to − 1
	0,7	+ 1

6.6 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 ISO 5167-1 : 1991. The geometric measure of eccentricity is the distance between the pipe and orifice plate centrelines 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 of 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 β = 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.
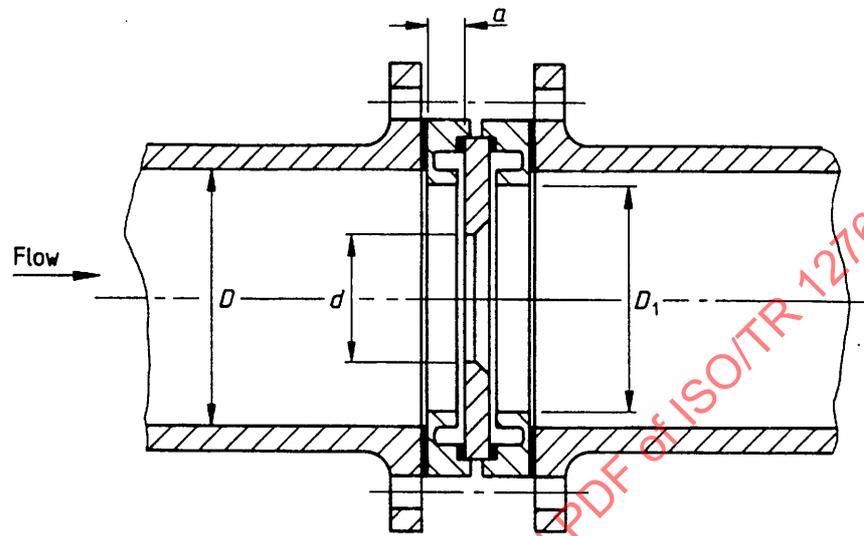
a) Orifice plate
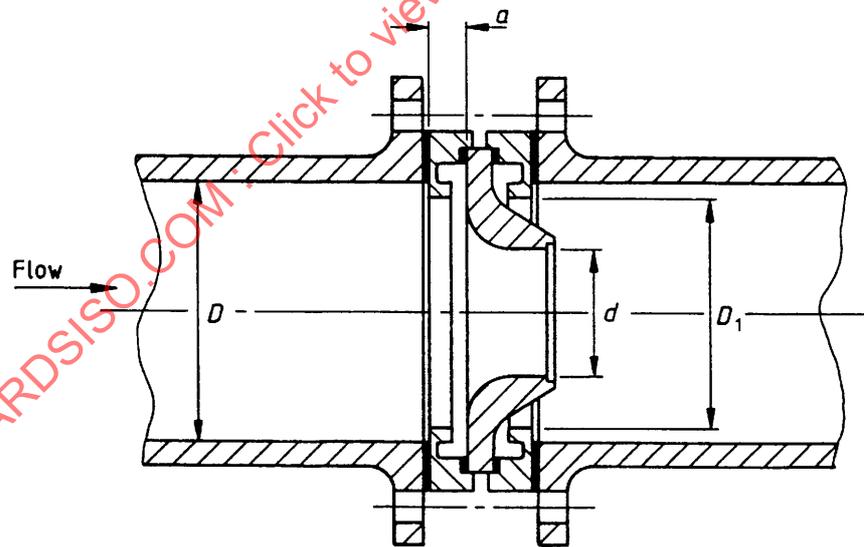
b) Nozzle

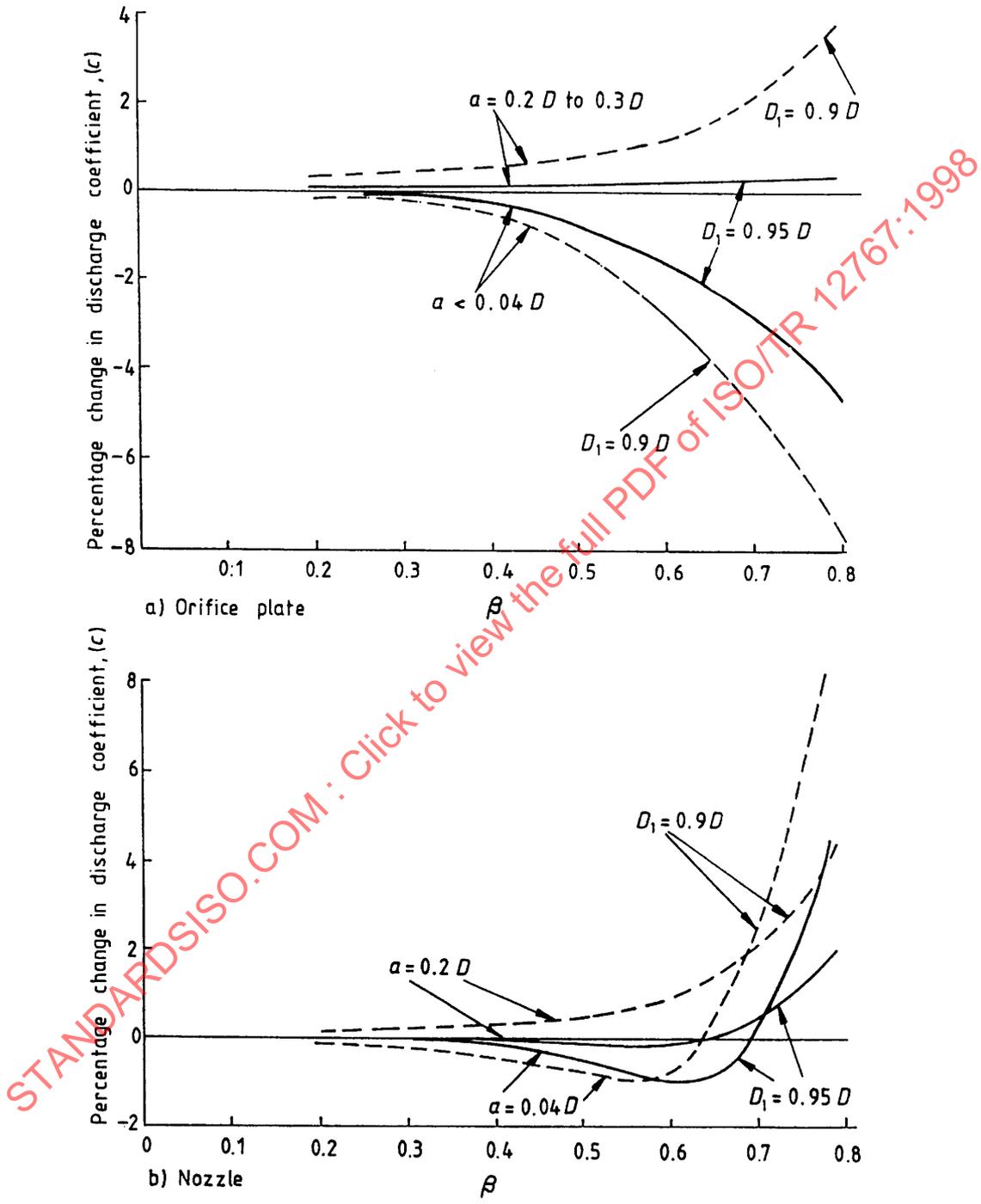**Figure 3 — Carrier having internal diameter, D_1, less than pipe diameter, D**

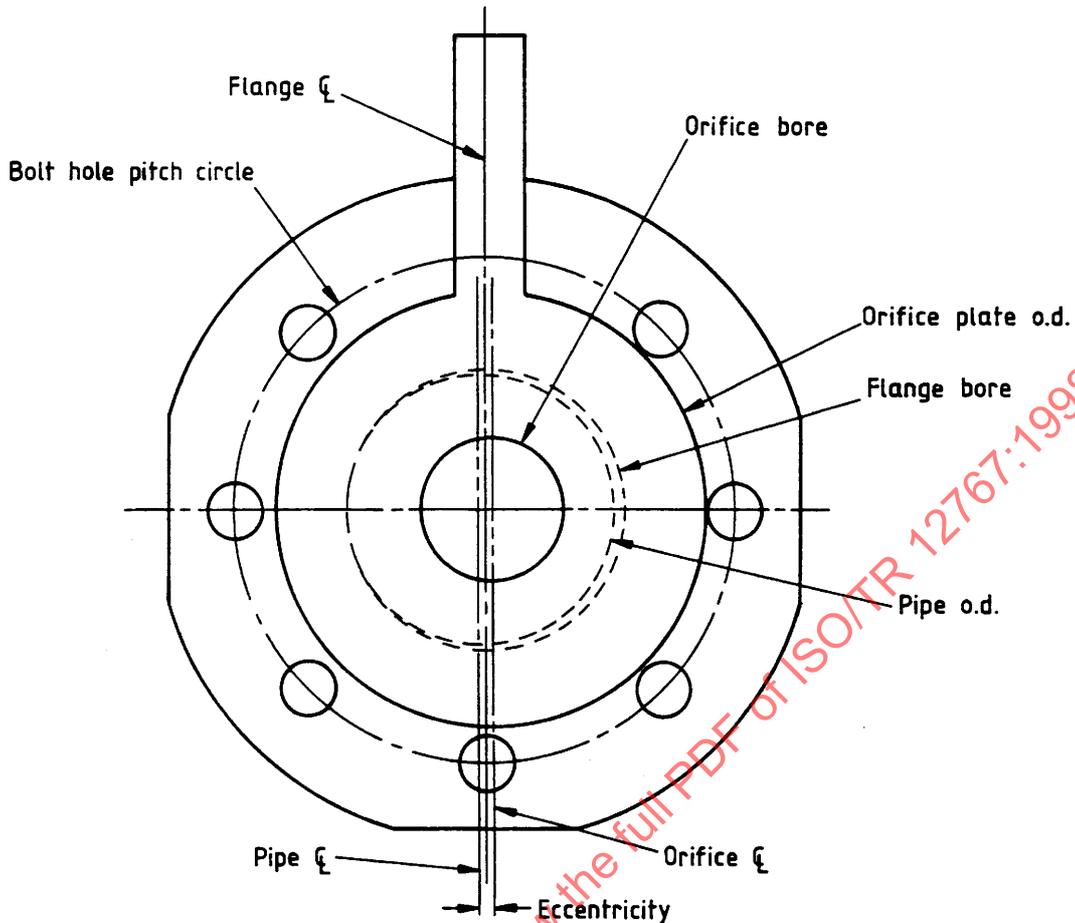Figure 4 — Effect of incorrect carrier diameter

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

ISO 5167-1 requires an arithmetic increase in discharge coefficient uncertainty of 0,3 % if the eccentricity lies between:

$$\frac{0,0025D}{0,1\ +\ 2,3\ \beta^4} \text{ and } \frac{0,005D}{0,1\ +\ 2,3\ \beta^4} \tag{6}$$

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.
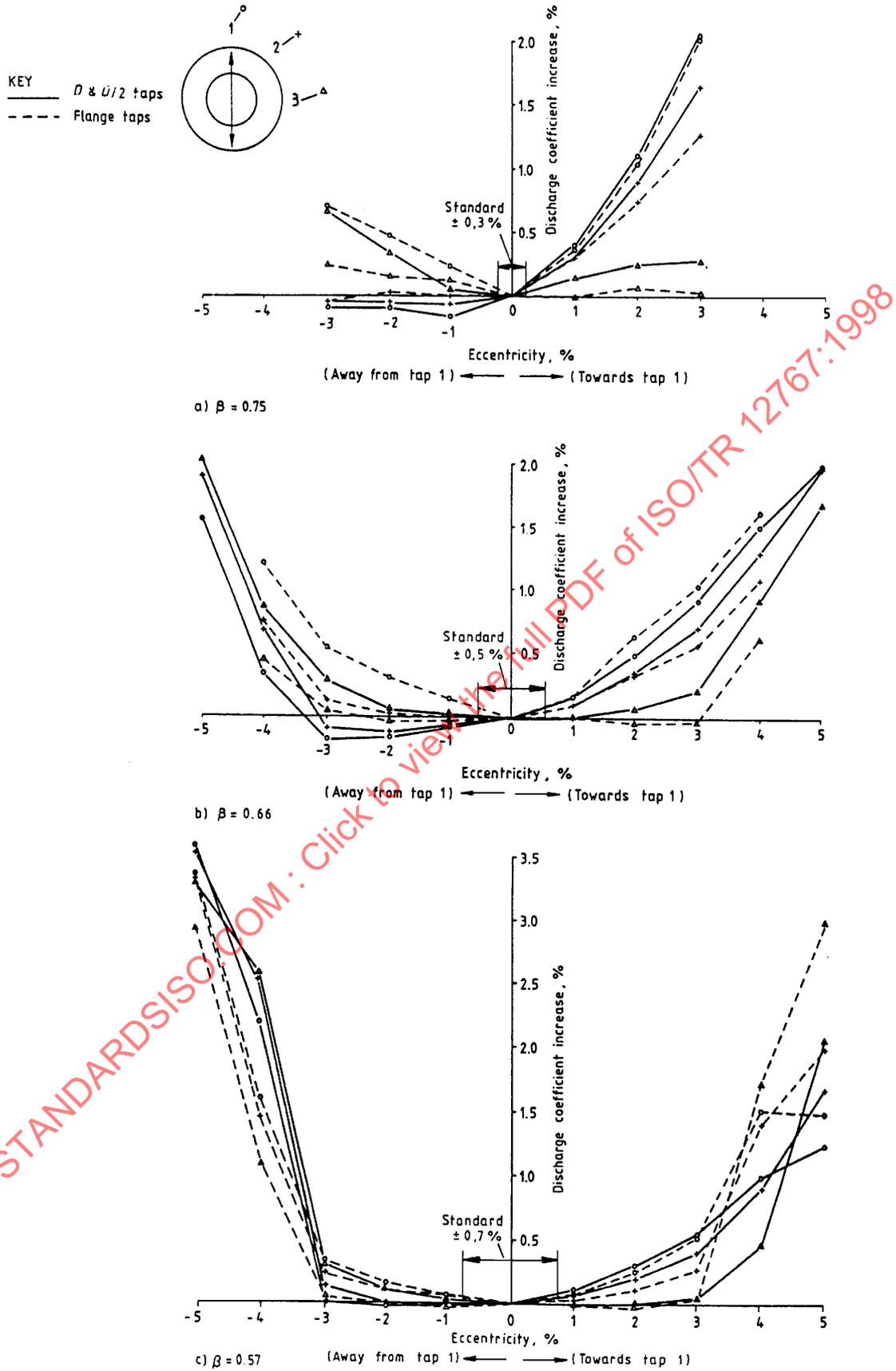
Figure 6 — Discharge coefficient error vs. eccentricity for an orifice plate with D and $D/2$ and flange taps
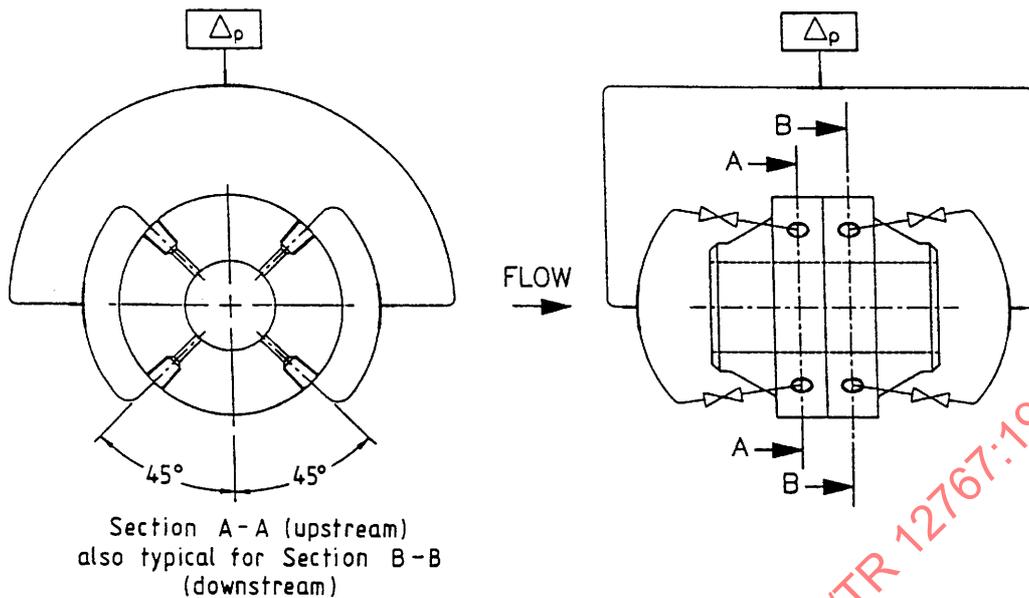
Figure 7 — Triple-T arrangements

7 Effects of pipe layout

7.1 General

Minimum values of the straight lengths required between the primary device and various upstream fittings are given in 7.2 of ISO 5167-1 : 1991. 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]

7.2 Discharge coefficient compensation

7.2.1 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.

Table 3 — Percentage discharge coefficient changes (_c_) when the straight pipe lengths before the orifice are less than those specified in 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 ISO 5167-1 : 1991.

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, 2/3 open	Corner flange
6	Two 90° bends at right angles, 5_D_ to 11_D_ spacer	All	15	Gate valve, 2/3 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 P 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 (1 − β)

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)	$0,5 (1 + \lvert c \rvert) + \dfrac{10}{X/D}$	$0,5 + \lvert c \rvert + \dfrac{10}{X/D}$
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.		

7.2.2 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:

$$e = 0,5 \, (1 + \lvert c \rvert) \tag{7}$$

where $\lvert c \rvert$ 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:

$$e = 0,5 + \lvert c \rvert \tag{8}$$

and if $c = -2,8$ %, then e = 3,3 %.

7.3   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.

7.4 Devices for improving flow conditions

Flow conditioners should always be used where asymmetric or swirling flow has to be measured. Subclause 7.3 of ISO 5167-1 : 1991 describes the installation position for five types of conditioners. If the conditioner cannot be installed as specified, or if the installation requirement in clause 7 of ISO 5167-1 : 1991 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.
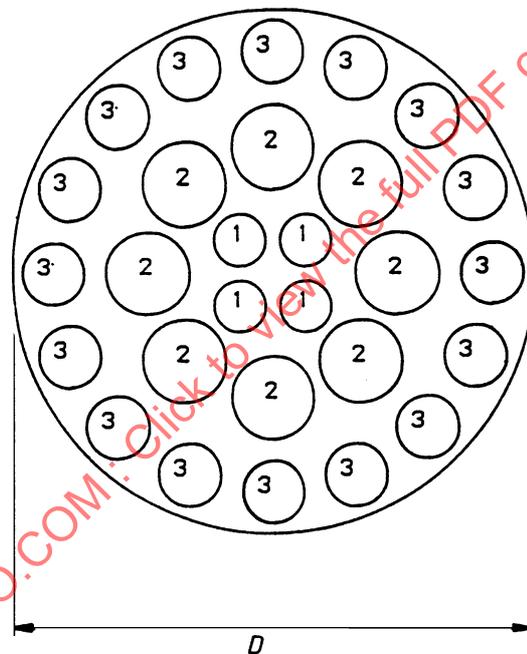

Plate thickness, $t = 0.12\,D$
Hole diameter, $d_1 = 0.10\,D$
Hole diameter, $d_2 = 0.16\,D$
Hole diameter, $d_3 = 0.12\,D$

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°
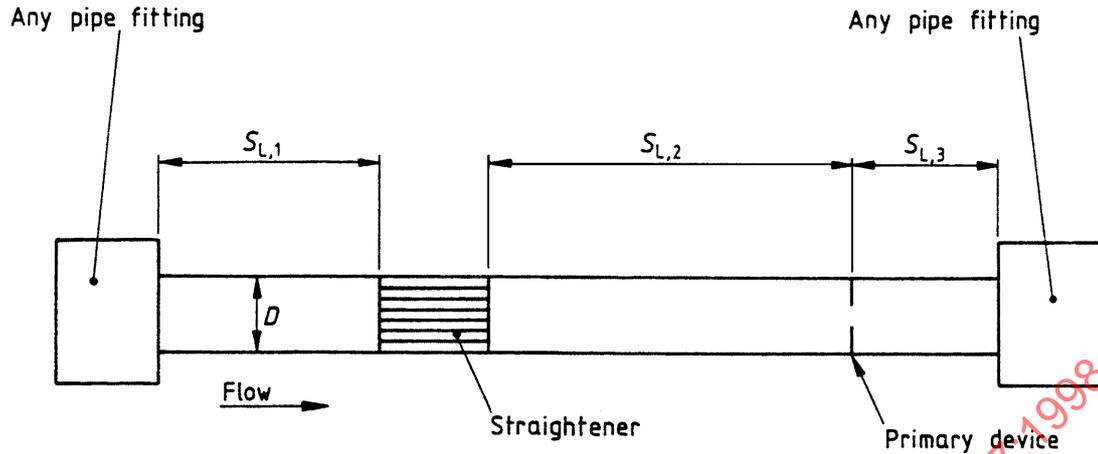
Figure 8 — The NEL flow conditioner

Figure 9 — Flow straightener installation

8 Operational deviations

8.1 General

Metering systems that conform to 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 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.

8.2 Deformation of an orifice plate

8.2.1 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 ISO 5167-1 : 1991. 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].

8.2.2 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:

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

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 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

8.2.3 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:

$$\Delta p_y = \sigma_y \left(\frac{E}{D_2} \right)^2 \left(\frac{1}{0,681 - 0,651 \, \beta} \right) \tag{10}$$
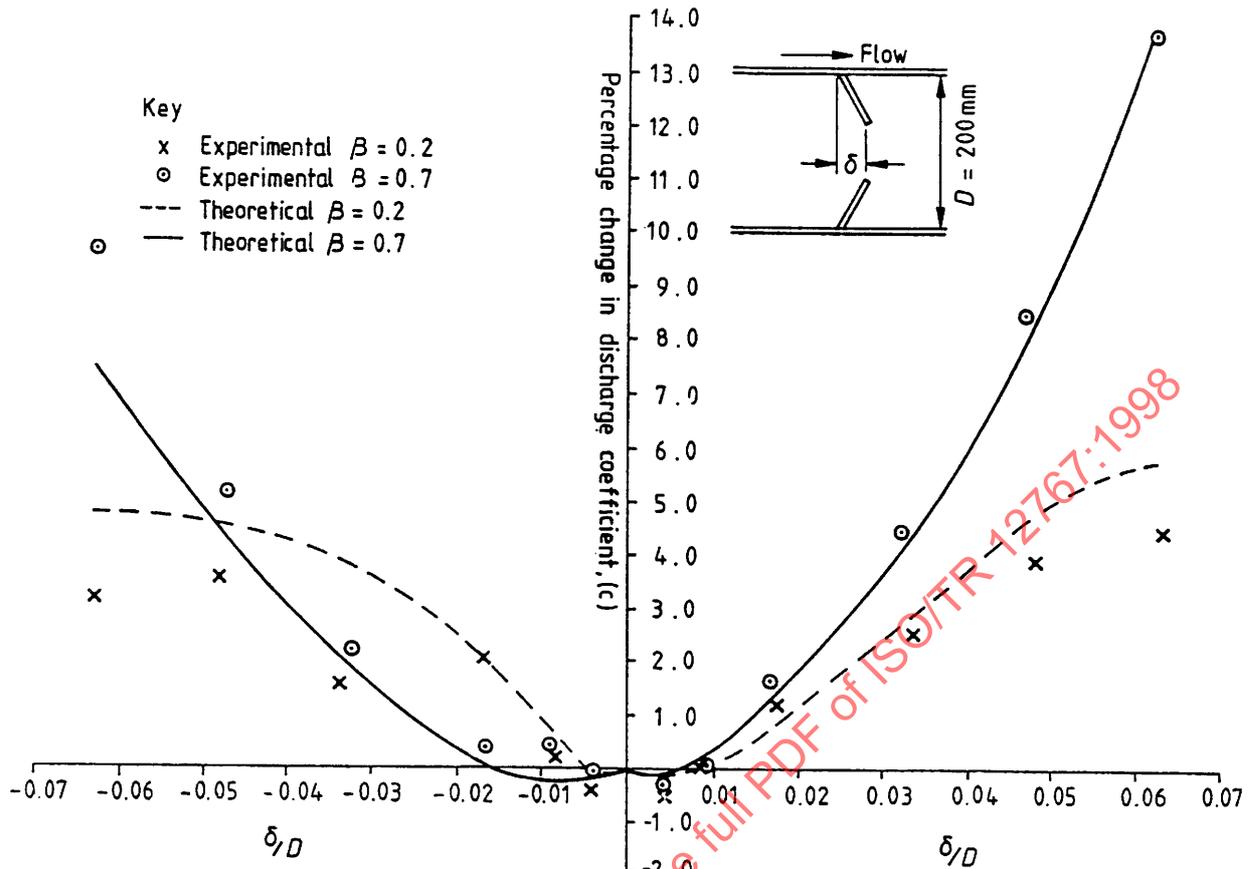
Figure 10 — Effect of orifice plate deformation on flow measurement accuracy

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 ISO 5167-1.

EXAMPLE:

a)   From equation (9) with $c = 0,1$

β = 0,2

Y = 193 x 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 x 10^6 Pa for stainless steel but for design purposes it is advisable to use

σ_y = 100 x 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.

8.3 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.

8.4 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.

8.5 Deposition and increase of surface roughness in Venturi tubes

8.5.1 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 8.5.2 and 8.5.3.

8.5.2 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:

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

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

8.5.3 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 Technical Report.

Table 6 — Effect of deposits on $\beta = 0,2$ and $\beta = 0,7$ orifice plates

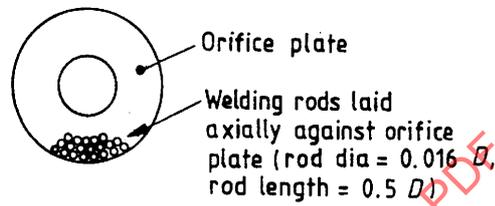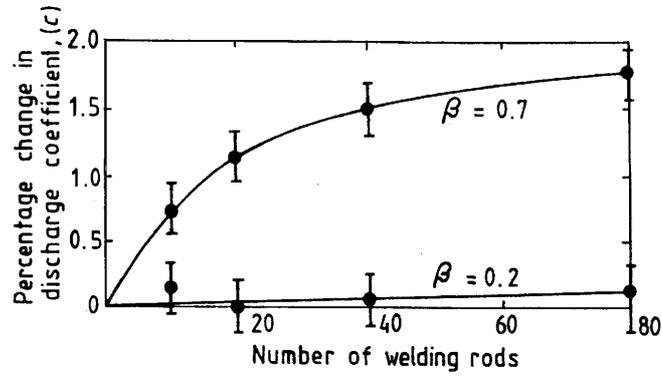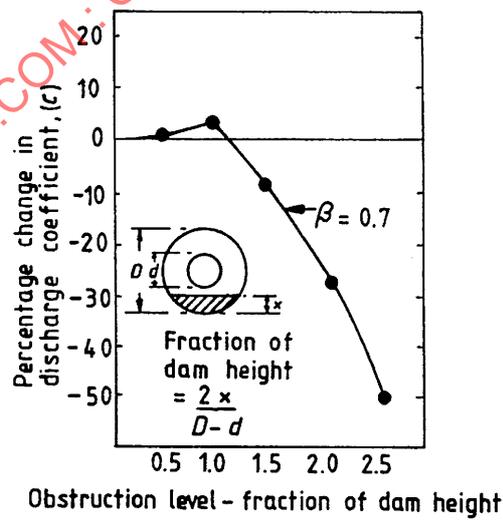| Deposit			Change in discharge coefficient	
			$\beta = 0,2$ %	$\beta = 0,7$ %
Sand	1 sand quadrant		+1,0	+0,8
	2 sand quadrants		+2,8	+1,9
	3 sand quadrants		+3,9	+2,4
	4 sand quadrants		+6,2	+3,0
	4 sand quadrants with 6 mm ring removed from around orifice bore		+0,3	+0,3
Grease	4 grease deposits		+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

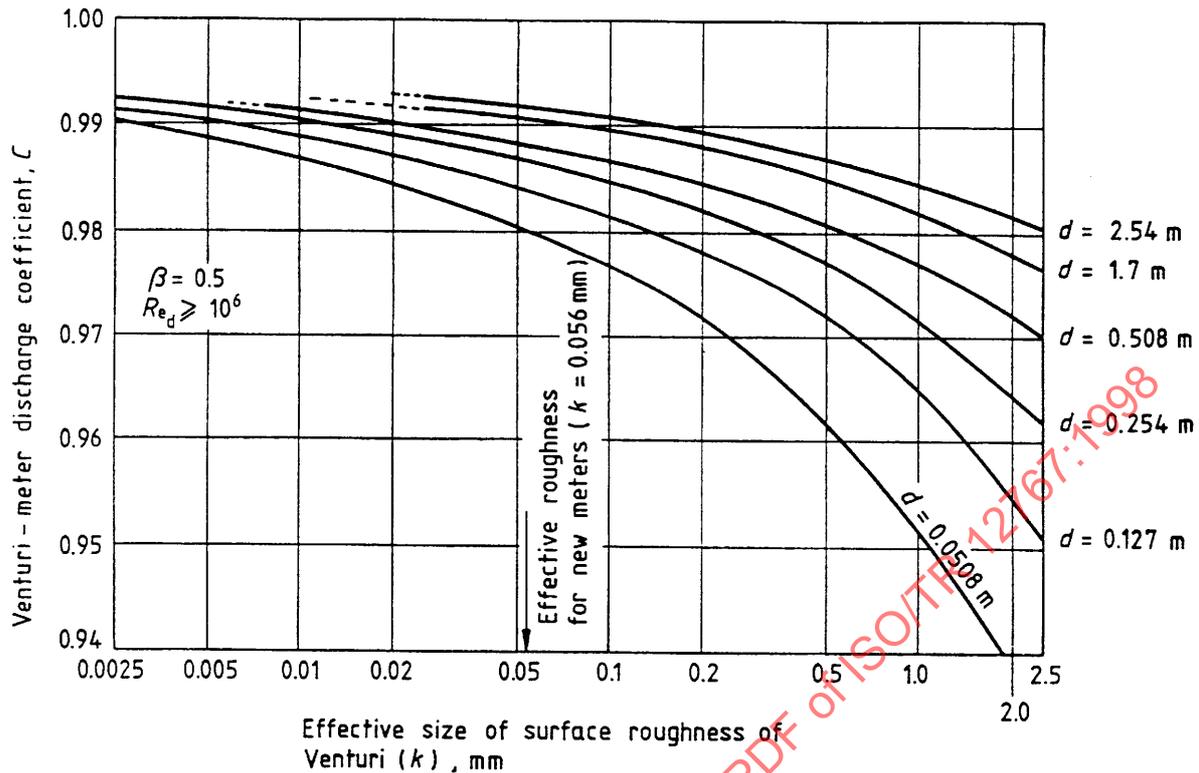**Figure 12 — Effect of debris in meter tube (on both sides of plate)**

Figure 13 — Variation of Venturi meter coefficient with surface roughness

8.6 Orifice-plate edge sharpness

8.6.1 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 5.1.

8.6.2 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.

9 Pipe roughness

9.1 General

The relationship between flowrate and pressure difference given in clause 3 of ISO 5167-1 : 1991 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:

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

u = Local velocity at y from pipe wall

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

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:

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

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

A more uniform profile ($U/u_{CL} \to 1$) 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.

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
$2,3 \times 10^4$	6,6	0,807	0,025
$1,1 \times 10^5$	7,0	0,817	0,0175
$1,1 \times 10^6$	8,8	0,850	0,0115
2×10^6	10	0,866	0,0105