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Orifice Plates with Drain Holes

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1 INTRODUCTION

Where a gas flow is continuously wet an orifice plate does not require a drain hole. However, a drain hole is appropriate where some liquid is introduced to the pipeline over a short period of time, but thereafter the gas flow is dry. In this case there is no need for wet-gas measurement; the problem is that during periods in which there is some liquid flow a pool of liquid will build up against the upstream face and thus the metering accuracy will be undermined even during the time when the flow is dry. Another installation where a drain hole was found appropriate was one where without a drain hole there was very significant accumulation of dirt; a new orifice plate with a drain hole allowed small particles of dirt to pass the plate and hence solved the problem.

The drain-hole solution provides a liquid bypass in the plate allowing liquids in a gas stream to pass through the plate. While drain-hole plates are a cost-effective way of measuring gas with a very low liquid content, they are not as accurate in single-phase flow as the standard design. As the extent of this inaccuracy is not well documented and as industry is sceptical of the existing formula, drain-hole plates are not as widely used as they might be: new data have therefore been needed to give confidence in their use.

ISO/TR 11583:2012 [1] covers wet-gas flow using orifice plates without drain holes. There is no accepted correlation for over-reading for orifice plates with drain holes in wet gas, and one is probably not needed. In many wet-gas flows through an orifice plate with a drain hole most of the liquid would pass through the orifice, not through the drain hole.

Figure 1 shows a picture of an orifice plate with a drain hole. The plate is fitted between the flanges using the bolt holes around the plate circumference. The dashed line visible in Fig. 1 marks out the area of the plate that is exposed to the fluid within the pipe.

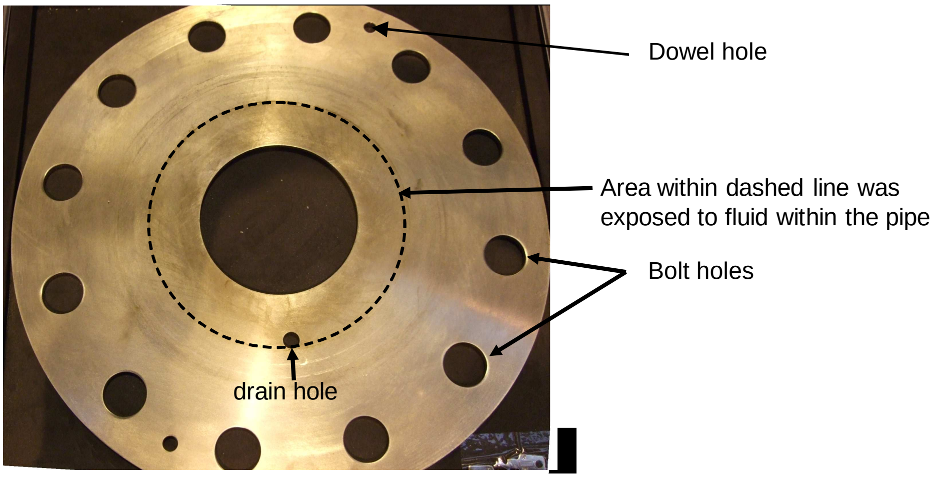


Fig. 1 Annotated picture of an orifice plate with a drain hole

The drain hole is a smooth circular hole through the plate located at the bottom of the pipe and with the bottom of the hole aligned with the bottom edge of the upstream pipe. The upstream edge of the drain hole should be sharp. The diameter of the downstream pipe at the orifice plate should be very similar to the upstream pipe: if the downstream pipe were much smaller than the upstream it would partially or completely block the drain hole. Alignment of the upstream pipe, the orifice plate and the downstream pipe is particularly important when there is a drain hole: for example, the dowel holes in Fig. 1 achieve this alignment.

There is a desire within industry to use orifice plates with drain holes, but ISO/TR 15377:2007 [2], the only reference document, is based on a very simple theoretical model: the measured orifice diameter, *d*, is corrected to a corrected orifice diameter, d_c, to allow for the additional flowrate due to the orifice area represented by the drain hole of diameter d_h as shown in the following equation:

$$d_c = d\left(1 + 0.55\left(\frac{d_h}{d}\right)^2\right) \qquad (1)$$

Equation (1) is based on the assumption that the value for $C\varepsilon(1 - \beta^4)^{-0.5}$ for flow through the drain hole is 10 % greater than the value for flow through the orifice. When Equation (1) is used to calculate the flowrate ISO/TR 15377:2007 states that the following additional percentage uncertainty should be added arithmetically to the discharge coefficient percentage uncertainty:

$$55\left(\frac{d_h}{d}\right)^2 . \qquad (2)$$

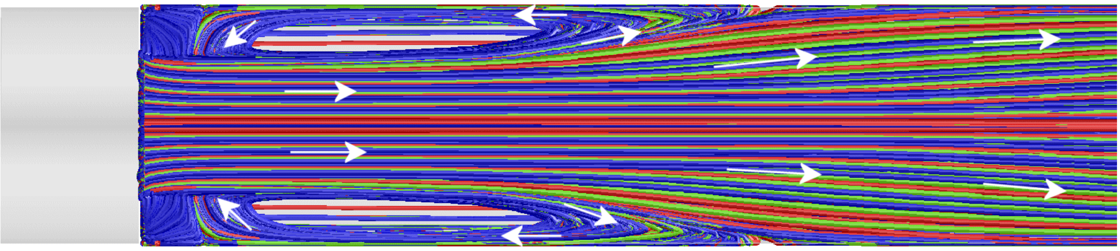
Since Equations (1) and (2) are not based on experiment there was a need for experimental data to improve the understanding of the physics of flow through drain holes and then to revise the standard.

The project started with a brief literature survey and contacts with those with relevant experience. No published experimental data were found. One contributor's experience was that drain holes as large as are permissible in ISO/TR 15377 were normal to avoid blockage, another's that drain holes either larger or smaller may be used, and another's that drain holes are typically 6 to 10 mm in diameter, regardless of pipe size. Although drain holes are sometimes not placed on the wall all contributors agreed that they should touch the wall. Blockage with solid material is a risk with drain holes and would not generally be detected but would lead to an error whose magnitude is equal to that of the drain hole correction.

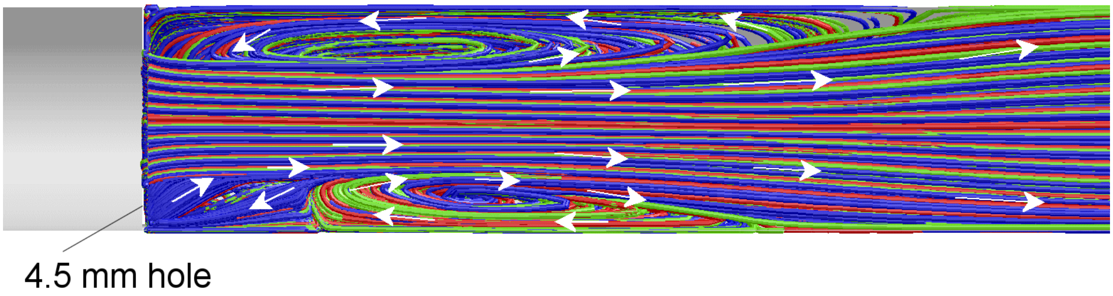
NOTE For β greater than around 0.4 (depending on drain hole size) a blockage could be detected if the differential pressure were measured using two pairs of tappings, one located on the top and the other on the side of the pipe: if the differential pressure were the same with the two pairs of tappings a blockage would be assumed (see Fig. 4).

The correction required when there is liquid flowing through the drain hole is unknown but it is assumed that the flow is nearly always dry; so no correction to the total measured flow is required to take account of the small fraction of the time when liquid is flowing.

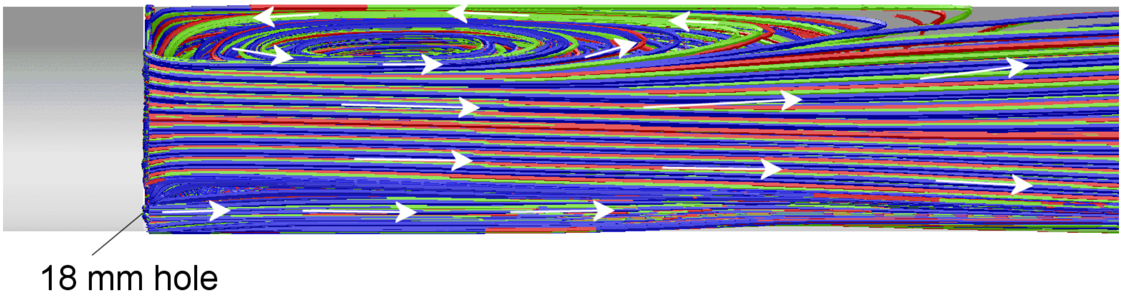
The significant disturbance that a drain hole makes to the flow pattern is well illustrated by computational work included in [3]: see Fig. 2.



a) No drain hole



b) 4.5 mm drain hole



c) 18 mm drain hole

Fig. 2 Streamlines Showing the Flow Pattern Downstream of a β = 0.6 Orifice Plate in a 6″ pipe

2 EXPERIMENTAL WORK: INITIAL DATA

In order to determine the effect of drain holes on orifice plates tests were carried out over a range of values of diameter ratio, β, drain hole diameter, d_h, pipe diameter, D, plate thickness, E, pipe Reynolds number, Re_D, and of tapping locations. These data were presented in [3] and [4].

The discharge coefficient, C, was obtained from the following equation:

$$q_m = \frac{C}{\sqrt{1-\beta^4}}\varepsilon\frac{\pi}{4}d^2\sqrt{2\Delta p \rho_1} \qquad (3)$$

where q_m is the mass flowrate of fluid, Δp is the differential pressure and ρ_1 the density at the upstream pressure tapping. ε is the expansibility as given by ISO 5167-2:2003. When a drain hole is included S, the percentage shift in C from that obtained with the same plate without a drain hole, was calculated. Note that the orifice diameter, d, is used for both calculations of discharge coefficient (not a corrected orifice diameter for the plate with a drain hole) and that throughout this paper β remains the ratio of orifice diameter, d, to pipe diameter. From physical considerations it is reasonable to expect that the key parameters are d_h/d, β, E/d_h, and L'_2, where $L'_2 = l'_2/D$ and l'_2 is the distance between the downstream face of the orifice plate and the downstream pressure tapping.

To achieve an appropriate pattern of test data an existing 4″ orifice run with flange and corner tappings was used with new plates with $\beta = 0.4$, 0.6 and 0.75. These three plates all had $E = 3$ mm. 3 mm is near the middle of the permissible range of values in ISO 5167-2:2003 [5]. In the US $E = \frac{1}{8}$ inch (3.175 mm) is normal for this pipe size. It seemed reasonable to suppose that thicker plates might make a difference, as the flow within the drain hole is more likely to reattach within a thicker plate (relative to d_h) than within a thinner one; so a plate with $\beta = 0.6$ and $E = 5$ mm was manufactured. Where $E/D = 0.05$ the plate was designated as thick.

The maximum permissible value of d_h/d in ISO/TR 15377:2007 is 0.1; so $d_h = 0.1d$ was tested together with $d_h = 0.07d$ and, where possible, a higher value of d_h too. The drain holes (like the orifices) were inserted using spark erosion (sometimes called Electrical Discharge Machining). All the plates with all the drain holes were tested in water, and, to examine whether there was an effect of Reynolds number, baselines and data with $d_h = 0.1d$ were obtained in gas (nitrogen) at nominal gauge pressures of 20 bar and 60 bar.

To determine the effect of pipe diameter an 8″ orifice run was constructed and tested in water with two orifice plates, $\beta = 0.42$ and 0.6. The internal diameter upstream of the orifice plate was 202.56 mm; that downstream of the plate was 202.65 mm.

Some of the data were taken with tappings on the side of the pipe (90° from the drain hole) or on the top of the pipe (180° from the drain hole), but some of the data were taken with tappings at 115° or 155° from the drain hole. All the shifts in discharge coefficient taken in water are shown in Tables 1 and 2. Where data were taken in water and in gas, that is in the 4″ pipe with $d_h/d = 0.1$, the shifts are shown in Table 3. Details of the test work and of the analysis are given in [3].

There were sufficient data to show that Equation (1), the equation in 5.1.2 of ISO/TR 15377:2007, creates a bias but not sufficient to produce a reliable equation. The work showed that the effect of Reynolds number was negligible, but that more data were required, especially for small β, for smaller E/D and for a wider range of pipe sizes.

Table 1 Percentage shifts in discharge coefficient in water: 4" data (without correcting the orifice diameter)

D (mm)	E/D	β	d_h/d	Percentage shift in discharge coefficient	
				Flange tappings at 115° from the drain hole	Corner tappings at 155° from the drain hole
102	0.03	0.4	0.07	0.751	0.913
102	0.03	0.4	0.1	1.249	1.612
102	0.03	0.6	0.07	0.840	1.528
102	0.03	0.6	0.1	1.456	2.578
102	0.03	0.6	0.167	3.487	5.163
102	0.05	0.6	0.07	0.892	1.583
102	0.05	0.6	0.1	1.575	2.778
102	0.05	0.6	0.167	3.662	5.429
102	0.03	0.75	0.07	1.590	2.330
102	0.03	0.75	0.1	2.266	3.508

Table 2 Percentage shifts in discharge coefficient in water: 8" data (without correcting the orifice diameter)

D (mm)	E/D	β	d_h/d	Percentage shift in discharge coefficient	
				Flange tappings at 180° from the drain hole	Flange tappings at 90° from the drain hole
203	0.03	0.42	0.1	1.512	1.258
203	0.03	0.603	0.1	2.234	1.306

Table 3 Percentage shifts in discharge coefficient for those drain holes (all $d_h/d = 0.1$) for which there are water and gas data: (without correcting the orifice diameter)

D (mm)	E/D	β	Tapping pair*	Percentage shift in discharge coefficient			
				Water	Gas (20 bar)	Gas (60 bar)	Water and gas
102	0.03	0.4	A	1.249	1.225	1.221	1.215
102	0.03	0.4	B	1.612	1.566	1.547	1.573
102	0.03	0.6	A	1.456	1.447	1.517	1.439
102	0.03	0.6	B	2.578	2.551	2.581	2.567
102	0.05	0.6	A	1.575	1.574	1.565	1.585
102	0.05	0.6	B	2.778	2.742	2.719	2.752
102	0.03	0.75	A	2.266	2.143	2.251	2.242
102	0.03	0.75	B	3.508	3.310	3.427	3.426

* Tappings: A: flange at 115° from drain hole; B: corner at 155° from drain hole

3 EXPERIMENTAL WORK: ADDITIONAL DATA

Additional data were then collected: in 8″ pipe β = 0.2, 0.6 and 0.75; in 2″ pipe β = 0.49 and 0.6. For the 8″ β = 0.6 data E/D = 0.02, since data with E/D = 0.03 and 0.05 had already been taken. The new data used flange tappings, were taken in water at NEL, and are shown in Table 4. The 2″ data were published by Spearman [6]. The orifice plates in 8″ pipe were calibrated using reference meters: the orifice plates were 70*D* downstream of a perforated-plate flow conditioner, itself preceded by around 10*D* of straight pipe. There was at least 20*D* of straight pipe downstream of the orifice plates. 9*D* of the straight pipe upstream of the orifice plate and at least 8*D* of that downstream were machined. At flanges within 29*D* of the orifice plate on the upstream side dowels and ‘O’ rings were used. The drain hole diameter, d_h, was chosen so that $d_h/d \le 0.1$. As before, the percentage shift in discharge coefficient is the change in discharge coefficient from that obtained with the same plate without a drain hole: the orifice diameter, d, is used for both calculations of discharge coefficient (not a corrected orifice diameter for the drain-hole plate).

The most surprising feature of the data is that the results have such a strong dependence on the circumferential location of the pressure tappings. Accordingly in the 8″ run tappings at 150°, 120° and 60° from the drain hole were added and more data obtained: these data are shown in Table 5. In practice, tappings at 60° would not be used. For the points in Table 5 the baseline discharge coefficient was taken from the baseline values with the same plate but with different tappings (also flange tappings). The plate was then rotated and more data obtained with tappings at 30° and 0° from the drain hole. The data at 0° from the drain hole were strongly affected by the flow past the tappings and are not shown, but those obtained with tappings at 30° from the drain hole are shown in Table 5 (the flow through the drain hole was shown to be unaffected by the presence of the tappings at 0° from the drain hole by the fact that the data at 60° and 90° from the drain hole were retaken and found to be within 0.05% of the values obtained without tappings at 0° from the drain hole).

Table 4 Percentage shifts in discharge coefficient in water (without correcting the orifice diameter)

D (mm)	E/D	β	d_h/d	% shift in discharge coefficient		
				Tappings at 90° from drain hole (on side)	Tappings at 180° from drain hole (on top)	
203	0.03	0.2	0.045	0.273	0.282	
203	0.03	0.2	0.07	0.626	0.649	
203	0.03	0.2	0.1	1.263	1.291	
203	0.02	0.6	0.045	0.306	0.54	
203	0.02	0.6	0.07	0.63	1.189	
203	0.02	0.6	0.1	1.257	2.196	
203	0.03	0.75	0.045	0.762	1.034	
203	0.03	0.75	0.07	1.341	2.037	
203	0.03	0.75	0.1	2.033	3.171	
52.5	0.06	0.489	0.039	0.225		*
52.5	0.06	0.489	0.104	1.369		*
52.5	0.06	0.6	0.032		0.279	*
52.5	0.06	0.6	0.1		2.12	*

* Paid for by CNR and published by Spearman [6]

Table 5 Percentage shifts in discharge coefficient in water (without correcting the orifice diameter)

D (mm)	E/D	β	d_h/d	Percentage shift in discharge coefficient			
				Tappings at 150° from drain hole	Tappings at 120° from drain hole	Tappings at 60° from drain hole	Tappings at 30° from drain hole
203	0.03	0.42	0.1	1.446	1.354	1.209	Not taken
203	0.02	0.6	0.1	2.046	1.708	0.911	0.885
203	0.03	0.75	0.1	3.085	2.817	0.807	-0.410

The errors in measured flowrate using Equation (1) (the equation in 5.1.2 of ISO/TR 15377:2007) and all the data in Tables 1, 2, 4 and 5 (except those with tappings at 30° from the drain hole and those with d_h/d = 0.167) are shown in Fig. 3, together with the uncertainty given by Equation (2) (from 5.1.2 of ISO/TR 15377:2007). It is clear that there is almost always an under-measurement (unless the tappings are at less than 90° from the drain hole) and that the under-measurement is often larger than the claimed uncertainty. The shift in discharge coefficient near the top of the pipe is much larger for large β than would have been expected given the size of the drain holes.

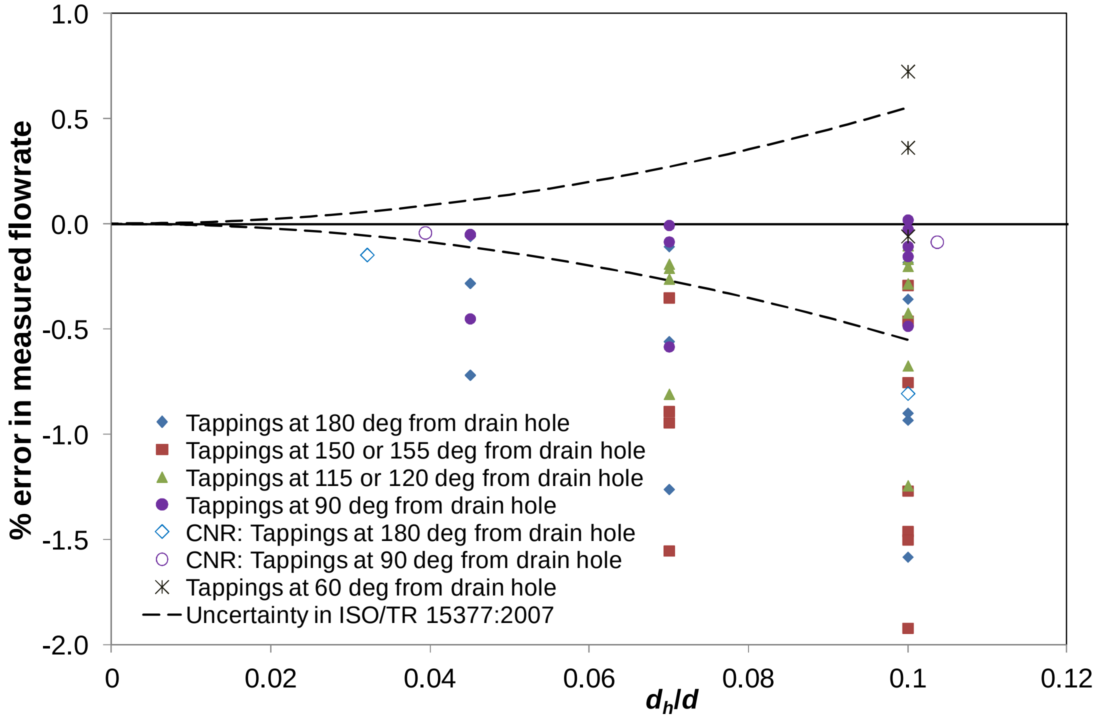


Fig. 3 Errors in measured flowrate using Equation (1) (the equation in 5.1.2 of ISO/TR 15377:2007)

The data in Table 5 together with the values with the same plates using tappings at 90° from the drain hole (on the side) and at 180° from the drain hole (on top) are plotted in Fig. 4. Additional data with plates with drain holes for which no baseline was available are also included in Fig. 4: baseline discharge coefficients taken from different plates made from the same drawings by the same manufacturer were used: their effect on the data in Fig. 4 is very small.

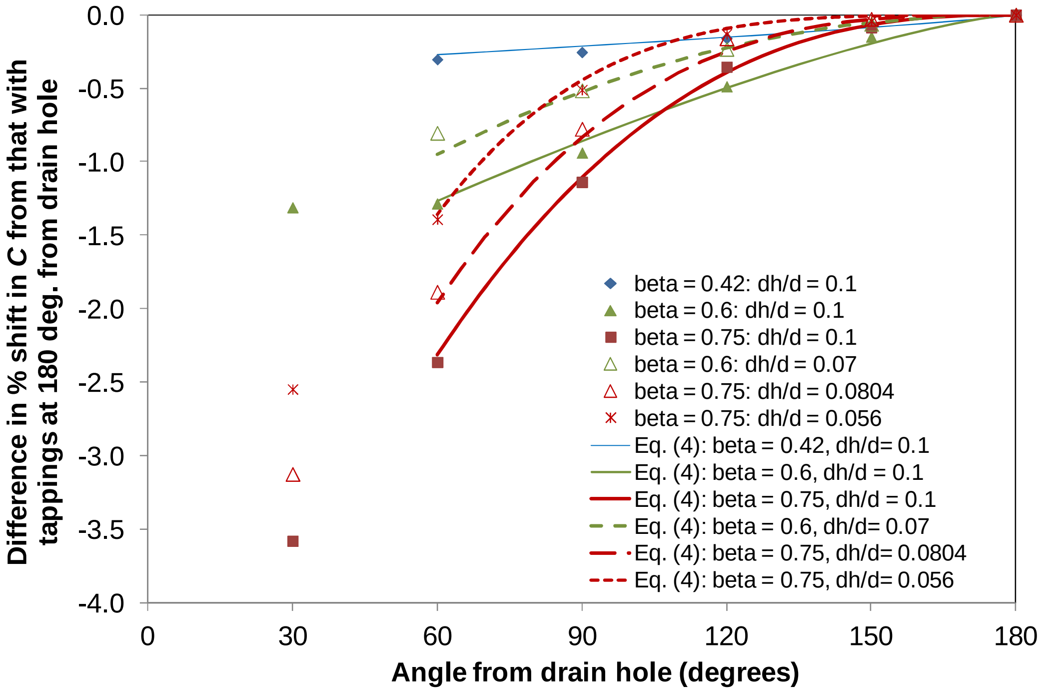


Fig. 4 Difference between percentage shift in *C* and percentage shift in *C* obtained with tappings at 180° from the drain hole: 8″ pipe with flange tappings

When the data in Fig. 4 from tappings at 60° or more from the drain hole were fitted, *S′*, the percentage shift in discharge coefficient less that obtained with tappings at 180° from the drain hole, was given by

$$S' = -26.8\beta^{4.9}\left(1-\frac{\theta}{180}\right)^{-0.95+7.5\beta^{4.9}+0.168\frac{d}{d_h}} \tag{4}$$

where θ is the angle from the drain hole (the bottom of the pipe) to the pressure tapping.

4 ANALYSIS

Applying Bernoulli's theorem and adding the flows through the orifice and the drain hole gives approximately

$$q_m = \frac{\frac{\pi}{4}d^2 C(Re_D,\beta'')\varepsilon(\beta'')\sqrt{2\rho_1(p_{up}-p_{dn,av})}}{\sqrt{1-\beta''^4}} + \frac{\frac{\pi}{4}{d_h}^2 C_h\varepsilon(\beta'')\sqrt{2\rho_1(p_{up}-p_{dn,btm})}}{\sqrt{1-\beta''^4}} \tag{5}$$

where

$$\beta'' = \beta\sqrt{1+\frac{C_h {d_h}^2}{Cd^2}}, \tag{6}$$

q_m is the total mass flowrate,
d_h is the drain hole diameter,

C is the discharge coefficient for the orifice with flange (or corner etc. as provided) tappings,
C_h is the discharge coefficient for the drain hole with the differential pressure obtained near the bottom of the pipe (0° from the drain hole),
ε is the expansibility factor,
p_{up} is the pressure at the upstream tapping,
$p_{dn,av}$ is the average pressure on the wall on the pipe circumference at the downstream flange (or corner etc. as provided) location,
$p_{dn,btm}$ is the pressure on the wall on the pipe circumference downstream of the drain hole near the bottom of the pipe (0° from the drain hole),
ρ_1 is the density at the upstream pressure tapping.

The definition of β'' takes account of the different velocities in the drain hole and in the orifice, although this effect is small. It is assumed that C and ε are unaffected by the presence of the drain hole, except for the effect of change in diameter ratio.

It might be that the discharge coefficient for the flow through the orifice is very different from $C(Re_D, \beta'')$ owing to asymmetry, for example. However, where the average differential pressure can be calculated Equation (5) is in fact remarkably accurate. Where C_h is taken from Equation (19) (to be derived later), the errors using Equation (5) are given in Table 6: they are 0.17% in magnitude at most.

NOTE If data were taken with tappings from 30° to 180° from the drain hole the wall pressure at 0° from the drain hole was calculated from those at 30° and 60° from the drain hole assuming that the wall pressure p_w is a quadratic in θ and that $\frac{\partial p_\mathrm{w}}{\partial \theta}$ = 0 at 0° from the drain hole; if data were taken with tappings from 60° to 180° from the drain hole the wall pressures at 0° and 30° from the drain hole were calculated from those at 60° and 90° from the drain hole assuming that p_w is a quadratic in θ and that $\frac{\partial p_\mathrm{w}}{\partial \theta}$ = 0 at 0° from the drain hole.

Table 6 Error in calculated flowrate using Equation (5) and the required angle from the drain hole for the tappings so that Equation (7) gives the true flowrate

D (mm)	E/D	β	d_h/d	% error in calculated flowrate using Equation (5)	Angle required for no error in flowrate using Equation (7)
203	0.03	0.42	0.1	-0.03	91.1°
203	0.02	0.6	0.1	-0.13	89.6°
203	0.03	0.75	0.1	-0.02	76.5°
203	0.03	0.6	0.07	0.05	94.1°
203	0.03	0.75	0.0804	0.17	78.6°
203	0.03	0.75	0.056	0.08	73.2°
203	0.03	0.6	0.1	Not available	85.1°

It is also possible to calculate the location for the downstream tapping at which the pressure could have been measured so that the error using Equation (7) is equal to zero, where Equation (7) is as follows:

$$q_m = \frac{\frac{\pi}{4} d^2 C(Re_D, \beta'') \varepsilon(\beta'') \sqrt{2\rho_1 (p_{up} - p_{dn,*})}}{\sqrt{1-\beta''^4}} + \frac{\frac{\pi}{4} {d_h}^2 C_h \varepsilon(\beta'') \sqrt{2\rho_1 (p_{up} - p_{dn,*})}}{\sqrt{1-\beta''^4}} \tag{7}$$

where

> $p_{dn,*}$ is the pressure at the downstream flange (or corner etc. as provided) location so that Equation (7) gives the true flowrate without angular correction.

These locations are given in Table 6. It is worth noting that where the angle has most effect (i.e. large β) on the shift in C there appears to be no effect of d_h/d on the angular location at which there is no error in flowrate using Equation (7).

Following the practice in ISO/TR 15377 the calculated flow is given by using a diameter d' such that

$$q_m = \frac{\frac{\pi}{4} d'^2 C(Re_D, \beta') \varepsilon(\beta') \sqrt{2\rho_1 (p_{up} - p_{dn,meas})}}{\sqrt{1-\beta'^4}} \tag{8}$$

where

$$\beta' = \frac{d'}{D}, \tag{9}$$

> $p_{dn,meas}$ is the measured pressure at the downstream flange (or corner etc. as provided) location.

It is necessary to provide a formula for d'. Equating Equations (5) and (8) gives

$$\frac{d'^2}{d^2} = \frac{C(Re_D, \beta'') \varepsilon(\beta'')}{C(Re_D, \beta') \varepsilon(\beta')} \sqrt{\frac{1-\beta'^4}{1-\beta''^4}} \left(\sqrt{\frac{p_{up} - p_{dn,av}}{p_{up} - p_{dn,meas}}} + \frac{{d_h}^2 C_h}{d^2 C} \sqrt{\frac{p_{up} - p_{dn,btm}}{p_{up} - p_{dn,meas}}} \right) \tag{10}$$

Since the second term is much smaller than the first the effect of change in diameter ratio on $\frac{C_h}{C}$ is negligible. Moreover, in the second (much smaller) term $p_{dn,btm}$ can be approximated by $p_{dn,av}$. Then Equation (10) becomes

$$\frac{d'^2}{d^2} = \frac{C(Re_D, \beta'') \varepsilon(\beta'')}{C(Re_D, \beta') \varepsilon(\beta')} \sqrt{\frac{1-\beta'^4}{1-\beta''^4}} \left(1 + \frac{{d_h}^2 C_h}{d^2 C} \right) \sqrt{\frac{p_{up} - p_{dn,av}}{p_{up} - p_{dn,meas}}} \tag{11}$$

From Equation (4) it might be reasonable to suppose that

$$p_{dn,meas} = p_{dn,top} - a\left(\beta, L_2', \frac{d_h}{d} \right) (p_{up} - p_{dn,av}) \left(1 - \frac{\theta}{180} \right)^n \tag{12}$$

where

> $p_{dn,top}$ is the pressure on the wall on the pipe circumference at the downstream flange (or corner etc. as provided) location at the top of the pipe (180° from the drain hole).

n might be a function of β, L_2' and $\frac{d_h}{d}$. The available data only require $n\left(\beta, \frac{d_h}{d}\right)$.

Equation (12) cannot be used for all θ, because as θ tends to 0 $\frac{\partial p}{\partial \theta}$ does not tend to 0; moreover, if *a* and *n* are estimated from Equation (4), as $\frac{d_h}{d}$ tends to 0 *p* becomes discontinuous and $p_{dn,btm}$ does not equal $p_{dn,top}$.

However, it is only necessary to assume that Equation (12) holds for $\theta \geq 60°$ and that θ^*, the value of θ at which the tappings should be placed to give the flowrate in accordance with Equation (7) (i.e. without correction for the angle from the drain hole), is the value of θ at which the average differential pressure round the circumference is measured. Then

$$p_{dn,av} = p_{dn,top} - a\left(\beta, L_2', \frac{d_h}{d}\right)(p_{up} - p_{dn,av})\left(1 - \frac{\theta^*}{180}\right)^n \tag{13}$$

Eliminating $p_{dn,top}$ between Equations (12) and (13) gives

$$p_{up} - p_{dn,meas} = (p_{up} - p_{dn,av})\left\{1 + a\left(1 - \frac{\theta}{180}\right)^n - a\left(1 - \frac{\theta^*}{180}\right)^n\right\} \tag{14}$$

Equation (11) becomes

$$\frac{d'^2}{d^2} = \frac{C(Re_D, \beta'')\varepsilon(\beta'')}{C(Re_D, \beta')\varepsilon(\beta')}\sqrt{\frac{1-\beta'^4}{1-\beta''^4}}\,\frac{1 + \dfrac{d_h{}^2 C_h}{d^2 C}}{\sqrt{1 + a\left(1 - \dfrac{\theta}{180}\right)^n - a\left(1 - \dfrac{\theta^*}{180}\right)^n}} \tag{15}$$

It remains to determine *a, n* and θ^*. From Equation (4) it is to be expected that *a* should be proportional to β^m. It is worth testing the possibility that *a* is proportional to $\left(\frac{d_h}{d}\right)^k$. As $\frac{l_2'}{d_h}\left(= \frac{L_2' d}{\beta d_h}\right)$ increases *a* should decrease, where l_2' is the distance from the downstream face of the orifice plate to the downstream tapping and $L_2' = \frac{l_2'}{D}$. Accordingly *a* might be expressed as

$$a = a'\beta^m\left(\frac{d_h}{d}\right)^k \exp\left(-a''\frac{L_2' d}{\beta d_h}\right). \tag{16}$$

Similarly from Equation (4) it is reasonable to expect that

$$n = n' + n''\beta^{m'} + n'''\frac{d}{d_h}. \tag{17}$$

From Table 6 it is reasonable to assume that

$$\theta^* = f - f'\beta^{f''}. \tag{18}$$

$$\frac{C_h}{C} \text{ is a function of } \frac{E}{d_h} \left(= \frac{dE}{\beta d_h D} \right).$$

For an orifice whose axis is the pipe axis the effect of changing the ratio of the orifice (bore) thickness *e* to the orifice diameter *d* is to change the orifice from a thin orifice, in which it is as if *e* were as close as possible to 0 given that a square edge is required on the orifice, to a thick orifice, whose discharge coefficient is approximately 0.8 when *e/d* is a little greater than 1, because the flow has now reattached to the orifice bore. The discharge coefficient changes slowly where *e/d* is small but more rapidly around *e/d* = 0.7. This is well exhibited in a set of data from NBS (now NIST) (see Lansverk [7]) given in Fig. 5.

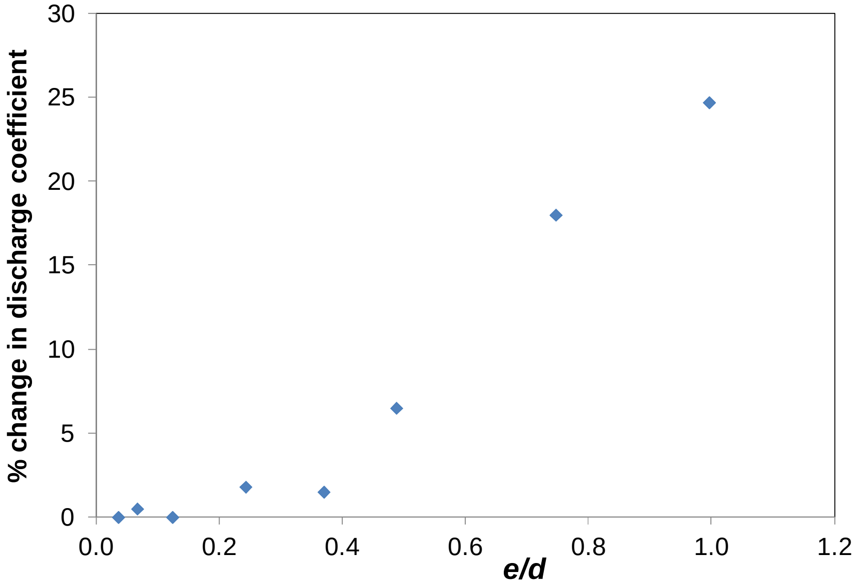


Fig. 5 Shift in discharge coefficient from the value where *e/d* is close to 0: 4″ β = 0.25 (no drain hole) from NBS (see Lansverk [7])

It is reasonable to suppose that for appropriate values of C', C'', r' and r''

$$\frac{C_h}{C} = \begin{cases} C' \quad \text{if} \quad E/d_h \le r' \\ \dfrac{C'(r'' - E/d_h) + C''(E/d_h - r')}{r'' - r'} \quad \text{if} \quad r' < E/d_h < r'' \\ C'' \quad \text{if} \quad r'' \le E/d_h \end{cases} \tag{19}$$

Since the discharge-coefficient data had been calculated as

$$q_{m,\text{true}} = \frac{\frac{\pi}{4} d^2 C(Re_D, \beta)\varepsilon(\beta)\sqrt{2\rho_1(p_{up} - p_{dn,meas})}}{\sqrt{1-\beta^4}} \left(1 + \frac{S}{100} \right) \tag{20}$$

where *S* is the percentage increase in discharge coefficient, from Equations (8) and (20) the percentage error in the measured flow is

$$100\left(\frac{d'^2 C(Re_D,\beta')\varepsilon(\beta')}{d^2 C(Re_D,\beta)\varepsilon(\beta)(1+0.01S)}\sqrt{\frac{1-\beta^4}{1-\beta'^4}}-1\right) \tag{21}$$

To determine the coefficients in Equations (16) and (17) a value of a'' was assumed, what the data points in Fig. 4 for $\theta \geq 60°$ would have been at $L_2' = 0$ was calculated, and then a', m, k, n', m', n'' and n''' were calculated (given that Fig. 4 is for changes in discharge coefficient, Equation (12) for changes in pressure). As might have been expected from Equation (4) no significant improvement was obtained with non-zero k or with m and m' unequal.

Then the data on percentage errors in measured flowrate were examined: there are many solutions with almost equal r.m.s. error. One solution is given below, in which the value of a'' has been used to refit the data in Fig. 4.

The coefficients are as follows:

$$a = 0.66\beta^{4.6}\exp\left(-0.15\frac{L_2' d}{\beta d_h}\right) \tag{22}$$

$$n = -0.45 + 7.3\beta^{4.6} + 0.117\frac{d}{d_h} \tag{23}$$

$$\theta^* = 92 - 62\beta^{4.6} \tag{24}$$

$$\frac{C_h}{C} = \begin{cases} 1.08 & \text{if} \quad E/d_h \leq 0.5 \\ 0.7675 + 0.625E/d_h & \text{if} \quad 0.5 \leq E/d_h \leq 0.9 \\ 1.33 & \text{if} \quad 0.9 \leq E/d_h \end{cases} \tag{25}$$

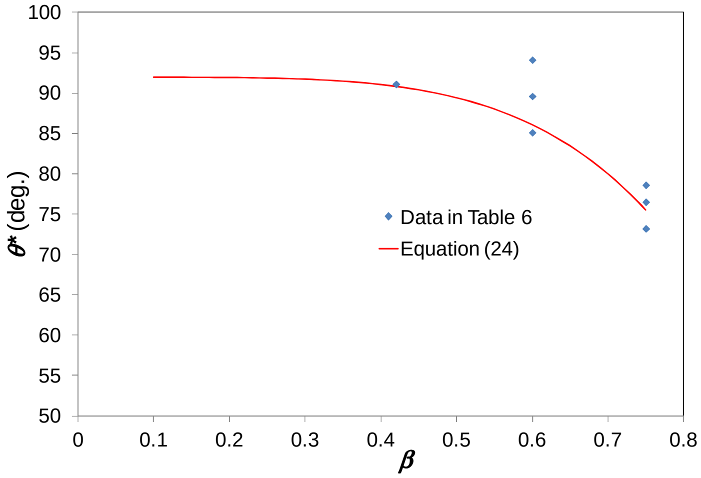


Fig. 6 Angle from drain hole at which a tapping should be placed to give a calculated flowrate without angular correction

Equation (24) gives quite good agreement with the data in Table 6: see Fig. 6. Equation (24) is fitted to a wider range of data than those plotted in the figure.

Equation (25) does not follow Fig. 5 exactly, but that is not surprising, since a drain hole is different from an orifice plate in that the fluid in a drain hole remains attached to the pipe wall.

Fig. 7 shows the points included in Fig. 4 compared with Equation (12) using the coefficients from Equations (22) and (23).

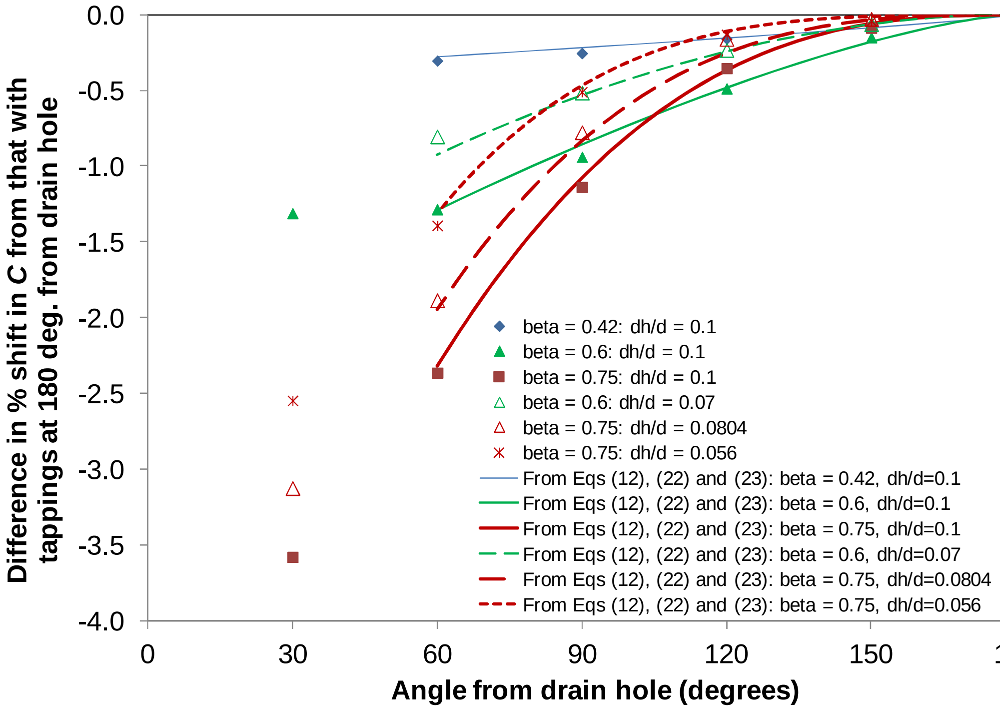


Fig. 7 Difference between percentage shift in *C* and percentage shift in C obtained with tappings at 180° from the drain hole: 8″ pipe with flange tappings

The errors in flowrate using Equations (15) and (22) to (25) for all the data in Tables 1, 2, 4 and 5 (except those at 30° from the drain hole) are given in Fig. 8. The data marked 'baseline from a similar plate' are additional data taken with plates with drain holes for which no baseline was available: these are the plates from which data are included in Fig. 4; baseline discharge coefficients taken from different plates made from the same drawings by the same manufacturer were used. Iteration was required to calculate d' using Equation (15). The standard deviation of the data for $\frac{d_h}{d} \leq 0.1$ is 0.104%. Shown on the graph is a possible uncertainty of $4\frac{d_h}{d}$ %. Data with $\frac{d_h}{d} > 0.1$ are shown, since they tend to confirm the form of the equation. However, the equation should not be used for $\frac{d_h}{d} > 0.1$.

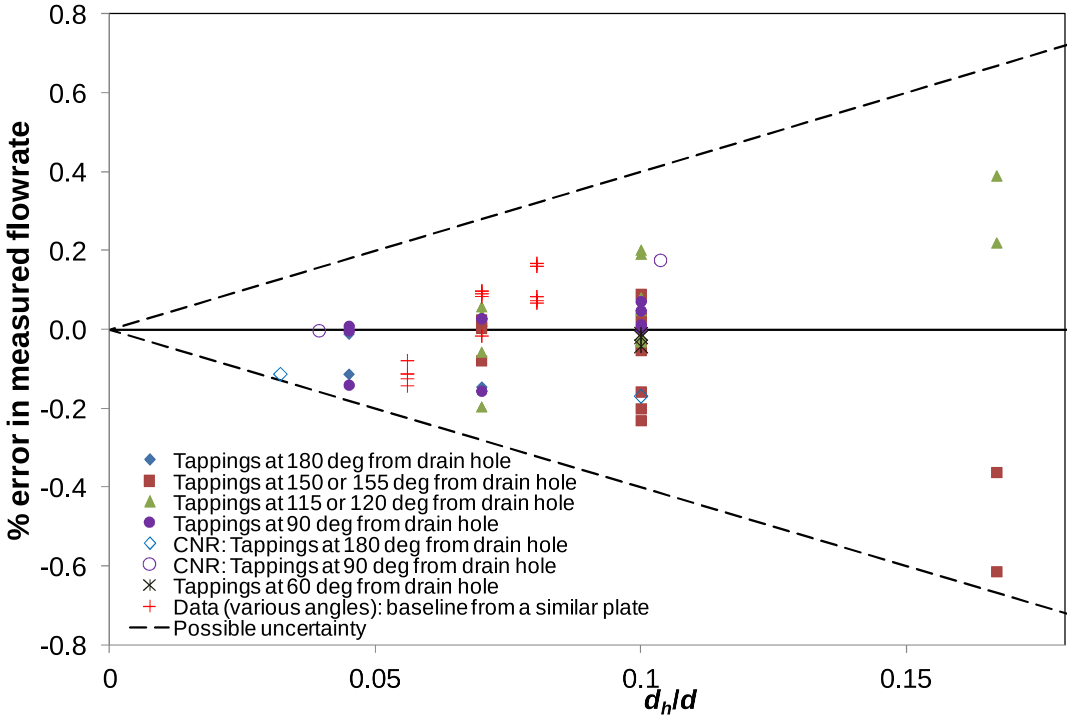


Fig. 8 Errors in measured flowrate using Equations (15) and (22) to (25)

In practice it is very desirable to have a fixed value for d' for an orifice plate with a drain hole (not a function of flowrate); to achieve this it would be necessary to use

$$\frac{d'^2}{d^2}=\frac{C(Re_D{}',\beta'')}{C(Re_D{}',\beta')}\sqrt{\frac{1-\beta'^4}{1-\beta''^4}}\;\frac{1+\dfrac{d_h{}^2C_h}{d^2C}}{\sqrt{1+a\left(1-\dfrac{\theta}{180}\right)^n-a\left(1-\dfrac{\theta^*}{180}\right)^n}} \qquad (26)$$

where $Re_D{}'$ is a fixed value of Reynolds number typical of the flow being measured but not the actual Reynolds number, Re_D, and a, n, θ' and $\frac{C_h}{C}$ are given in Equations (22) to (25) and β'' in Equation (6). In high-pressure gas flows $Re_D{}'$ might be taken as, say, 4 × 10^6. Then if $10^6 < Re_D < 5\times10^7$ the error in flowrate due to the use of a fixed Reynolds number of $Re_D{}'$ equal to 4 × 10^6 is less than 0.013% in magnitude for the values of β' and β'' used in this analysis. From Equation (5) of ISO 5167-2:2003, if $\Delta p/p_{\mathrm{up}}$ < 0.02 and the isentropic exponent κ > 1.25 the error in flowrate due to omitting the expansibility ratio term is less than 0.014% in magnitude (if $\Delta p/p_{\mathrm{up}}$ < 0.05 and κ > 1.25 the error in flowrate due to omitting the expansibility ratio term is less than 0.036% in magnitude).

The number of iterations to convergence using Equation (26) can be reduced by rearranging the equation to bring β' and d' to the same side of the equation:

$$\frac{d'}{d}=\frac{1}{\left\{\left(1-\beta''^4\right)\left(\frac{C(Re_D',\beta')}{C(Re_D',\beta'')}\right)^2\frac{\left(1+a\left(1-\frac{\theta}{180}\right)^n-a\left(1-\frac{\theta*}{180}\right)^n\right)}{\left(1+\frac{d_h{}^2C_h}{d^2C}\right)^2}+\beta^4\right\}^{0.25}} \qquad (27)$$

Moreover, if $\beta \le 0.63$ or $\beta \le 0.7$ and $\theta = 90°$ the ratio of discharge coefficients $\frac{C(Re_D',\beta')}{C(Re_D',\beta'')}$ can be taken as equal to 1 with an error in flowrate of 0.016% or less in magnitude: in this case there is no need to iterate: Equation (27) becomes

$$\frac{d'}{d}=\frac{1}{\left\{\left(1-\beta''^4\right)\frac{\left(1+a\left(1-\frac{\theta}{180}\right)^n-a\left(1-\frac{\theta*}{180}\right)^n\right)}{\left(1+\frac{d_h{}^2C_h}{d^2C}\right)^2}+\beta^4\right\}^{0.25}} \quad \begin{array}{c}\text{for } \beta\le 0.63 \text{ or}\\ \beta\le 0.7 \text{ and } \theta=90^\circ\end{array} \qquad (28)$$

Equation (28) gives good results for the whole database, but there is insufficient evidence to use it for all situations.

5 CONCLUSIONS

Recent data show that the existing drain-hole equation in ISO/TR 15377:2007 is unsatisfactory. The data on drain holes have a surprisingly strong dependence on the circumferential location of the pressure tappings, although very little dependence on Reynolds number. A new analysis is presented based on the assumption that, although the differential pressure itself is disturbed by the presence of the drain hole, the discharge coefficient for the orifice is unaffected by its presence provided that the mean differential pressure is used. On this basis Equation (27) has been produced for d', the corrected orifice diameter taking account of the drain hole. More data would be good, but it is very desirable to amend ISO/TR 15377:2007, given that its equation leads to flowrate errors up to nearly 2% in magnitude, whereas the new equation gives errors less than 0.25% in magnitude.

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NOTATION

C	Discharge coefficient
C_h	Discharge coefficient for a drain hole
d	Diameter of orifice
d_c	Corrected orifice diameter to allow for the additional flowrate due to a drain hole following ISO/TR 15377:2007
d_h	Diameter of drain hole
d'	Corrected orifice diameter to allow for the additional flowrate due to a drain hole
D	Upstream internal pipe diameter
e	Orifice bore thickness
E	Orifice plate thickness
l_2'	Spacing from the downstream face of the orifice plate to the downstream pressure tapping
L_2'	Spacing from the downstream face of the orifice plate to the downstream pressure tapping divided by the pipe diameter ($= l_2'/D$)
p	Absolute static pressure of the fluid
$p_{dn,av}$	Average absolute static pressure on the wall on the pipe circumference at the downstream flange (or corner etc. as provided) location
$p_{dn,btm}$	Absolute static pressure on the wall on the pipe circumference downstream of the drain hole near the bottom of the pipe (0° from the drain hole)
$p_{dn,meas}$	Absolute static pressure measured at the downstream flange (or corner etc. as provided) location
$p_{dn,top}$	Absolute static pressure on the wall on the pipe circumference at the downstream flange (or corner etc. as provided) location at the top of the pipe (180° from the drain hole)
$p_{dn,*}$	Absolute static pressure at the downstream flange (or corner etc. as provided) location so that Equation (7) gives the true flowrate without angular correction
p_{up}	Absolute static pressure at the upstream tapping
q_m	Mass flowrate
Re_D	Reynolds number referred to D
S	Percentage shift in discharge coefficient
β	Diameter ratio: $\beta = d/D$
Δp	Differential pressure
ε	Expansibility [expansion] factor
θ	Angle between tappings and drain hole
θ^*	Value of θ at which the tappings should be placed to give a calculated flowrate without correction for the angle from the drain hole
κ	Isentropic exponent
ρ_1	Density of the fluid at upstream pressure tapping

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