Orifice plates with drain holes

Dr Michael Reader-Harris and David Addison
NEL
East Kilbride, GLASGOW, UK, G75 0QF
mreader@tuvnel.com

Abstract

This paper presents new data and shows that the existing drain-hole equation in ISO/TR 15377 is unsatisfactory: it leads to flowrate errors up to nearly 2% in magnitude. The data on drain holes have a surprisingly strong dependence on the circumferential location of the pressure tappings. However, a new analysis takes this into account and has produced a formula for *d'*, the corrected orifice diameter taking account of the drain hole. It is very desirable to amend ISO/TR 15377:2007.

Introduction

Despite recent advances in other flow metering technologies, the simplicity, reliability and low capital cost of the orifice plate have ensured that it remains the instrument of choice for many applications. It is by far the most common flow meter in industrial service, accounting for over 40 per cent of the market, across a wide range of sectors including oil and gas, process, energy and chemical. However, where an orifice plate is used to meter a gas flow, the presence of small quantities of entrained liquid can present a problem as, if steps are not taken to allow the liquid to pass the plate, a pool will build up against the upstream face and undermine the metering accuracy.

One solution is to provide a liquid bypass in the form of a drain hole 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.

It is important to state that in a flow in which there is a significant continuous flow of liquid a drain hole is not required. ISO/TR 11583 [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.

A drain hole is appropriate where some liquid is introduced to the pipeline over a short period of time, but thereafter the flow is dry. In this case there is no need for wet-gas measurement; however, it is essential that there is no error in the dry-gas flow due to a pool of liquid that never passes through the orifice. 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 solved the problem.

There is a desire within industry to use orifice plates with drain holes, but ISO/TR 15377 [2], the only reference document, is based on a very simple theoretical model, and 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.

Data on orifice plates with drain holes were collected and published in [3]: 4” β = 0.4, 0.6 and 0.75 and 8” β = 0.42 and 0.6 data were taken; 4” β = 0.6 data with E/D = 0.05 were taken in addition to data with the typical E/D = 0.03. D is the pipe internal diameter, d is the orifice diameter, β ($=\frac{d}{D}$) is the diameter ratio, and E is the plate thickness. In the earlier data most of the data had flange tappings, but some of the 4” data had corner tappings. Some of the data were taken with tappings on the side of the pipe (90° to the drain hole) or on the top of the pipe (180° to the drain hole), but some of the data were taken with tappings at 115° or 155° to the drain hole. There were sufficient data to show that the equation in 5.1.2 of ISO/TR 15377:2007 creates a bias but not sufficient to produce a reliable equation.

New data

Since the publication of [3] additional data have been collected: 8” β = 0.2, 0.6 and 0.75; 2” 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 2” data were published by CNR [4]. All the new data use flange tappings, were taken in water at NEL, and are shown in Table 1. The drain hole diameter, d_h, was chosen so that $d_h/d \leq 0.1$. 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° to the drain hole were added and data obtained: these data are shown in Table 2. In practice, tappings at 60° would not be used. Tappings at 30° or 0° might have disturbed the flow near the drain hole. For the points in Table 2 the baseline discharge coefficient was taken from the baseline values with the same plate but with different tappings in the same planes.

Table 1 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 on side (90° to drain hole)	% shift in discharge coefficient: Tappings on top (180° to drain hole)	
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		CNR
52.5	0.06	0.489	0.104	1.369		CNR
52.5	0.06	0.6	0.032		0.279	CNR
52.5	0.06	0.6	0.1		2.12	CNR

Table 2 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° to drain hole	Percentage shift in discharge coefficient: Tappings at 120° to drain hole	Percentage shift in discharge coefficient: Tappings at 60° to drain hole
203	0.03	0.42	0.1	1.446	1.354	1.209
203	0.02	0.6	0.1	2.046	1.708	0.911
203	0.03	0.75	0.1	3.085	2.817	0.807

The errors in measured flowrate using the equation in 5.1.2 of ISO/TR 15377:2007 and all the data in [3] and in Tables 1 and 2 are shown in Figure 1, together with the uncertainty given in 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.

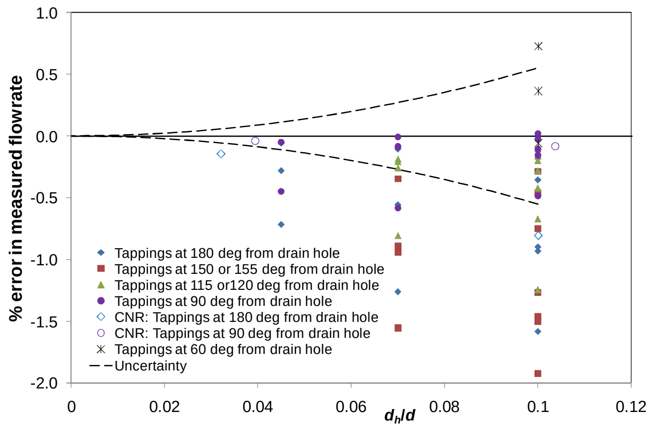

Figure 1 Errors in measured flowrate using the equation in 5.1.2 of ISO/TR 15377:2007

The data in Table 2 together with the values with the same plates using tappings on the side and on top are plotted in Figure 2. Additional data with plates with drain holes for which no baseline was available are also included in Figure 2. Baseline discharge coefficients taken from different plates made from the same drawings by the same manufacturer were used: their effect on the data in Figure 2 is very small.

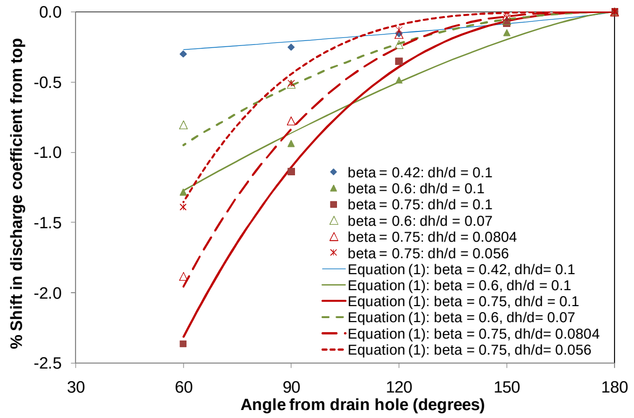

Figure 2 % shift in discharge coefficient from the value obtained with flange tappings on the top: 8" pipe

When the data in Figure 2 are fitted, *S'*, the percentage shift in discharge coefficient from the value obtained with tappings on the top, is given by

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

where θ is the angle from the drain hole (the bottom of the pipe) to the pressure tapping. The shift in discharge coefficient is much larger than would have been expected given the size of the drain holes.

Analysis

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

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

where

$$\beta'' = \beta\sqrt{1+\frac{C_h d_h^2}{C d^2}},$$

q_v is the total volumetric 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 flange (or corner etc. as provided) tappings at the bottom of the pipe,
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 at the downstream flange (or corner etc. as provided) location at the bottom of the pipe,
ρ is the density.

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. In the subsequent analysis the need for this refinement was not clear; presumably any effects were absorbed in other terms. The simple fit appears to work surprisingly well.

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

$$q_V = \frac{\frac{\pi}{4} d'^2 C(Re_D, \beta') \varepsilon(\beta')}{\sqrt{1-\beta'^4}} \sqrt{\frac{2(p_{up} - p_{dn,meas})}{\rho}} \qquad (3)$$

where

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

$p_{dn,meas}$ 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 (2) and (3) gives

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

Since the second term is much smaller than the first the effect of change in diameter ratio on $\frac{C_h}{C}$ is negligible.

From Equation (1) it might be reasonable to suppose that

$$p_{dn,meas} = p_{dn,top} - a\left(\beta, L_2', \frac{d_h}{d}\right)(p_{up} - p_{dn,av})\left(1 - \frac{\theta}{180}\right)^n \qquad (5)$$

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.

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

However, the weakness of this approach is that as θ tends to 0 $\frac{\partial p}{\partial \theta}$ does not tend to 0; moreover, if a and n are calculated from Equation (1), as $\frac{d_h}{d}$ tends to 0 p becomes discontinuous and $p_{dn,btm}$ does not equal $p_{dn,top}$.

A possible solution is to assume that

$$p_{dn,meas} = p_{dn,top} - a(p_{up} - p_{dn,av}) \times \begin{cases} \left(1 - \frac{\theta}{180}\right)^n & (60^\circ \le \theta \le 180^\circ) \\ \left(\frac{2}{3}\right)^n \left(1 + \frac{n}{2f}\left(1 - \left(\frac{\theta}{60}\right)^f\right)\right) & (0^\circ \le \theta < 60^\circ) \end{cases} \qquad (6)$$

This has $\frac{\partial p}{\partial \theta} = 0$ at $\theta = 0$ provided that $f > 1$ and gives p and $\frac{\partial p}{\partial \theta}$ continuous at $\theta = 60°$. Provided that n tends to ∞ as $\frac{d_h}{d}$ tends to 0 $p_{dn,btm}$ becomes equal to $p_{dn,top}$.

Integrating Equation (6) gives

$$p_{dn,av} = p_{dn,top} - a\left(\frac{2}{3}\right)^n \left(\frac{n+3}{3(n+1)} + \frac{n}{6(f+1)}\right)(p_{up} - p_{dn,av}) \qquad (7)$$

Substituting from (7) into (5) and simplifying gives

$$\frac{p_{up} - p_{dn,meas}}{p_{up} - p_{dn,av}} = \begin{cases} 1 - a\left\{\left(\frac{2}{3}\right)^n \left(\frac{n+3}{3(n+1)} + \frac{n}{6(f+1)}\right) - \left(1 - \frac{\theta}{180}\right)^n\right\} & (60^\circ \le \theta) \\ 1 + an\left(\frac{2}{3}\right)^n \left\{\frac{2}{3(n+1)} + \frac{2f+3}{6f(f+1)} - \frac{1}{2f}\left(\frac{\theta}{60}\right)^f\right\} & (\theta < 60^\circ) \end{cases} \qquad (8)$$

Substituting $\theta = 0$ into Equation (8) gives

$$\frac{p_{up} - p_{dn,btm}}{p_{up} - p_{dn,av}} = 1 + an\left(\frac{2}{3}\right)^n \left\{\frac{2}{3(n+1)} + \frac{2f+3}{6f(f+1)}\right\} \qquad (9)$$

Dividing Equations (8) and (9) gives, for 60° ≤ θ ≤ 180°,

$$\frac{p_{up} - p_{dn,btm}}{p_{up} - p_{dn,meas}} = \frac{1 + an\left(\frac{2}{3}\right)^n \left(\frac{2}{3(n+1)} + \frac{2f+3}{6f(f+1)}\right)}{1 - a\left\{\left(\frac{2}{3}\right)^n \left(\frac{n+3}{3(n+1)} + \frac{n}{6(f+1)}\right) - \left(1 - \frac{\theta}{180}\right)^n\right\}} \qquad (10)$$

Substituting Equations (8) and (10) into Equation (4) gives, for 60° ≤ θ ≤ 180°,

$$\frac{d'^2}{d^2} = \frac{C(Re_D,\beta'')\varepsilon(\beta'')}{C(Re_D,\beta')\varepsilon(\beta')}\sqrt{\frac{1-\beta'^4}{1-\beta''^4}}$$
$$\times\frac{\left\{1+\frac{d_h{}^2 C_h}{d^2 C}\sqrt{1+an\left(\frac{2}{3}\right)^n\left(\frac{2}{3(n+1)}+\frac{2f+3}{6f(f+1)}\right)}\right\}}{\sqrt{1-a\left\{\left(\frac{2}{3}\right)^n\left(\frac{n+3}{3(n+1)}+\frac{n}{6(f+1)}\right)-\left(1-\frac{\theta}{180}\right)^n\right\}}} \quad (11)$$

It remains to determine a and n. From Equation (1) 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 to the downstream tapping and $L_2' = \frac{l_2'}{D}$. Accordingly a might be expressed as

$$a = a'\beta^m\left(\frac{d_h}{d}\right)^k \exp\left(-a''\frac{L_2' d}{\beta d_h}\right) \quad (12)$$

Similarly from Equation (1) it is reasonable to expect that

$$n = n' + n''\beta^{m'} + n'''\frac{d}{d_h} \quad (13)$$

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

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 for e/d = 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 = 0.6. This is well exhibited in a set of data from NBS (now NIST) (see [5]) given in Figure 3.

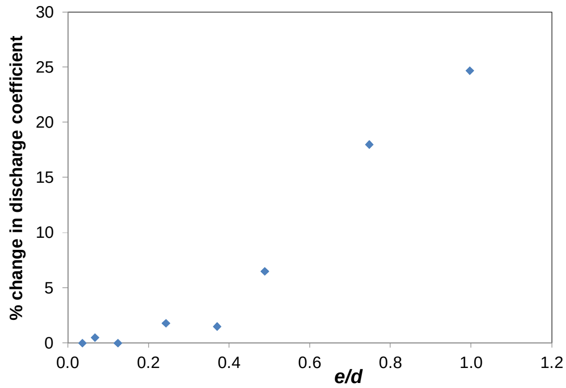

Figure 3 Shift in discharge coefficient from the value where *e/d* is close to 0: 4" β = 0.25 from NBS (see [5])

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

$$\frac{C_h}{C} = \begin{cases} C' & \text{if} \quad d_h/E \le r' \\ \frac{C'(r''-d_h/E)+C''(d_h/E-r')}{r''-r'} & \text{if} \quad r' < d_h/E < r'' \\ C'' & \text{if} \quad r'' \le d_h/E \end{cases} \quad (14)$$

Since the discharge-coefficient data had been calculated as

$$q_{V,\text{true}} = \frac{\frac{\pi}{4}d^2 C(Re_D,\beta)\varepsilon(\beta)}{\sqrt{1-\beta^4}}\sqrt{\frac{2(p_{up}-p_{dn,meas})}{\rho}}\left(1+\frac{S}{100}\right) \quad (15)$$

where S is the percentage increase in discharge coefficient, from Equations (3) and (15) the percentage error in the measured flow is

$$100\left(\frac{d'^2 C(Re_D,\beta')\varepsilon(\beta')}{d^2 C(Re_D,\beta)\varepsilon(\beta)(1+0.01S)}\sqrt{\frac{1-\beta^4}{1-\beta'^4}}-1\right) \quad (16)$$

To determine the coefficients in Equations (12) and (13) a value of a'' was assumed, what the data points in Figure 2 would have been at L_2' = 0 was calculated, and then a', m, k, n', m', n'' and n''' were calculated (given that Figure 2 is for changes in discharge coefficient, Equation (5) for changes in pressure). As might have been expected from Equation (1) 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 and the errors minimized: a'', f, C', C'', r' and r'' were determined. Then the value of a'' was used to refit the data in Figure 2 and the process repeated to convergence.

After rounding the coefficients are as follows:

$$a = 0.66\beta^{4.6}\exp\left(-0.15\frac{L_2' d}{\beta d_h}\right) \quad (17)$$

$$n = -0.45 + 7.3\beta^{4.6} + 0.117\frac{d}{d_h} \quad (18)$$

$$f = 2 \quad (19)$$

$$\frac{C_h}{C} = \begin{cases} 1 & \text{if} \quad E/d_h \le 0.3 \\ 0.85 + 0.5E/d_h & \text{if} \quad 0.3 < E/d_h < 0.9 \\ 1.3 & \text{if} \quad 0.9 \le E/d_h \end{cases} \quad (20)$$

Equation (20) does not follow Figure 3 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.

Figure 4 shows the points included in Figure 2 but with Equations (5) and (6) compared. Collection of more data would be required to show that Equation (6) actually fits the data for θ < 60° as well as providing a good model for the data for θ ≥ 60°.

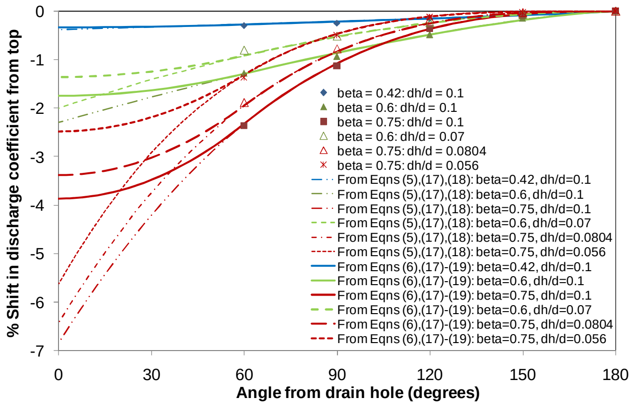

Figure 4 % shift in discharge coefficient from the value obtained with flange tappings on the top: 8" pipe

The errors in flowrate using Equations (11) and (17) to (20) are given in Figure 5. Iteration is required to calculate d' using Equation (11). Shown on the graph is a possible uncertainty of $4\dfrac{d_h}{d}$ %.

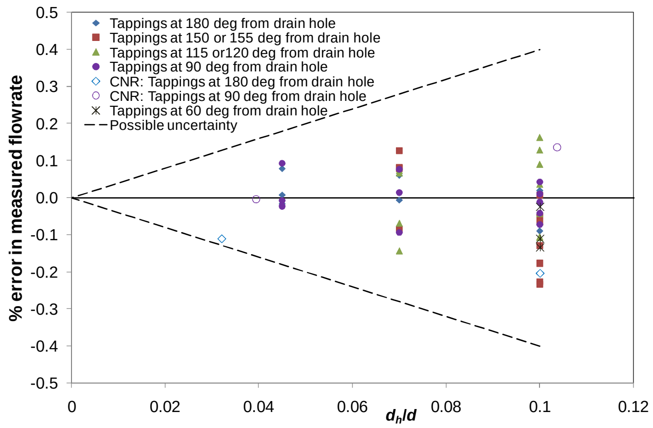

Figure 5 Errors in measured flowrate using Equations (11) and (17) to (20)

In practice it is very desirable to have a fixed value for d' (not a function of flowrate); so it would be necessary to use (with *f* put equal to 2)

$$\frac{d'^2}{d^2} = \frac{C(Re_D', \beta'')}{C(Re_D', \beta')}\sqrt{\frac{1-\beta'^4}{1-\beta''^4}} \times \frac{\left\{1+\dfrac{d_h^2 C_h}{d^2 C}\sqrt{1+an\left(\dfrac{2}{3}\right)^n\left(\dfrac{2}{3(n+1)}+\dfrac{7}{36}\right)}\right\}}{\sqrt{1-a\left\{\left(\dfrac{2}{3}\right)^n\left(\dfrac{n+3}{3(n+1)}+\dfrac{n}{18}\right)-\left(1-\dfrac{\theta}{180}\right)^n\right\}}} \qquad (21)$$

where Re_D' is, say, 4×10^6 for high-pressure gas flows, where $a, n, \dfrac{C_h}{C}$ are given in Equations (17) to (18) and (20) and β'' just below Equation (2). If $10^6 < Re_D < 5\times10^7$ the error due to the use of a fixed Reynolds number is less than 0.012% in magnitude for the values of β' and β'' used in the analysis. If $p_2/p_1 > 0.98$ and $\kappa > 1.25$ the error due to omitting the expansibility ratio term is less than 0.014% in magnitude.

The number of iterations to convergence using Equation (21) can be reduced by rearranging the equation to bring β' and d' to the same side of the equation:

$$\left(\frac{d'}{d}\right)^{-4} = \left(1-\beta''^4\right)\left(\frac{C(Re_D', \beta')}{C(Re_D', \beta'')}\right)^2 \times \frac{\left(1-a\left\{\left(\dfrac{2}{3}\right)^n\left(\dfrac{n+3}{3(n+1)}+\dfrac{n}{18}\right)-\left(1-\dfrac{\theta}{180}\right)^n\right\}\right)}{\left\{1+\dfrac{d_h^2 C_h}{d^2 C}\sqrt{1+an\left(\dfrac{2}{3}\right)^n\left(\dfrac{2}{3(n+1)}+\dfrac{7}{36}\right)}\right\}^2} + \beta^4 \qquad (22)$$

Conclusions

This paper presents new data and shows that the existing drain-hole equation in ISO/TR 15377 is unsatisfactory. The data on drain holes have a surprisingly strong dependence on the circumferential location of the pressure tappings. However, a new analysis has taken this into account and has produced Equation (22) 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.

Acknowledgments

The work described in this paper was carried out as part of the National Measurement Office's Engineering and Flow Programme, under the sponsorship of the United Kingdom Department for Business, Innovation and Skills.

This paper is published by permission of the Managing Director, NEL.

References

[1] International Organization for Standardization. Measurement of wet gas flow by means of pressure differential devices inserted in circular cross-section conduits. ISO/TR 11583:2012. Geneva..

[2] International Organization for Standardization. Measurement of fluid flow by means of pressure-differential devices – guidelines for the specification of orifice plates, nozzles and Venturi tubes beyond the scope of ISO 5167. ISO/TR 15377:2007. Geneva.

[3] Reader-Harris, M. J., Hodges, D., and Rushworth, R. "The effect of drain holes in orifice plates on the discharge coefficient", in Proc. 26th International North Sea Flow Measurement Workshop, St Andrews, Fife, Oct. 2008.

[4] Spearman, E. P. "Operational measurement experiences in North Sea applications", in Proc. 30th International North Sea Flow Measurement Workshop, St Andrews, Fife, Oct. 2012.

[5] Lansverk, N. B. "Effects of abnormal conditions on accuracy of orifice measurement", ISHM, 1990.