The effect of contaminated orifice plates on the discharge coefficient

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Abstract: Orifice plates can be contaminated by oil, grease, pipeline sludge or other liquids or solids. Experience shows that sometimes the contamination extends to the sharp edge of the orifice plate, but that on many occasions any possible contamination near the edge is cleaned by the flow. The latter case is investigated here. In some of the existing sets of data the contamination in the form of soft deposits used to gather the data means that interpretation is not straightforward; so Computational Fluid Dynamics (CFD) was used to assist in the interpretation.

In the experimental work the contamination was simulated by sticking circular metal discs of defined thickness and radius to the plates so as to leave an untouched region in the neighbourhood of the sharp edge. The effect of this contamination was measured in nitrogen at 63 bar absolute. CFD was used to investigate similar contaminated plates.

A contamination angle was defined, and the CFD predictions were plotted against the contamination angle. The simulations for a diameter ratio, β, equal to 0.6, almost lie on a single curve. The β = 0.2 and β = 0.4 points lie above this curve and the β = 0.75 points lie below the curve. The new NEL experimental data are compared with the CFD and the Advantica data on coated plates with a clean ring as in ISO/TR 12767.

It is clear from the experimental data, as indeed from the CFD, that although the ratio of the thickness of the contamination to the distance from the orifice edge is the most important effect on the shift it is not the only effect. An equation for the percentage shift in discharge coefficient was derived to fit the experimental data: this has an uncertainty of 0.28 % based on 2 standard deviations. The CFD are in remarkably good agreement with the experiments and support the inclusion of the new model in a revision of ISO/TR 12767.

Keywords: Differential-pressure meters, Orifice plates, Contamination

1 Introduction

Despite recent advances in other flow metering technologies, the simplicity, reliability and 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, orifice plates can be contaminated by oil, grease, pipeline sludge or other liquids or solids. This causes problems in the UK national gas transmission system and in many process applications. The effect of contamination on the discharge coefficient has been measured by a number of companies and some of the data are in the public domain[1, 2]. However, the soft deposits used in these tests mean that interpretation is not straightforward; so it was proposed that Computational Fluid Dynamics (CFD) should be used to assist in the interpretation.

On the basis of the computational results described below experiments were carried out to verify the model.

2 Computational work

A series of computational fluid dynamics (CFD) simulations were run representing orifices plates with varying degrees of contamination on the front face. Simulations were run using ANSYS Fluent 6.3 CFD software[3].

Plates with diameter ratios of 0.2, 0.4, 0.6 and 0.75 were modelled, with the pipe diameter *D* set to 300 mm. Flange tappings were used for all cases.

The operating fluid was defined as being an incompressible gas of density 28 kg/m^3 and a viscosity of 1.7 x 10^{-5} Pa s. 35 simulations were run at a pipe Reynolds number of 10^7. The remaining three runs were at 10^6.

The majority of the simulations used a two-dimensional axisymmetric domain and represented an orifice plate with a uniform layer of contamination on the front face of thickness *h*, a distance *r* from the orifice edge, as shown in Figure 1.

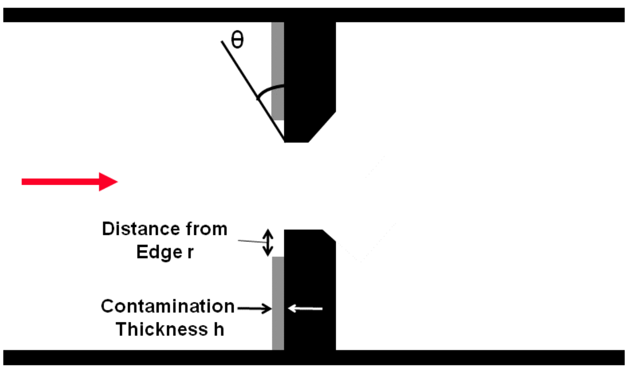
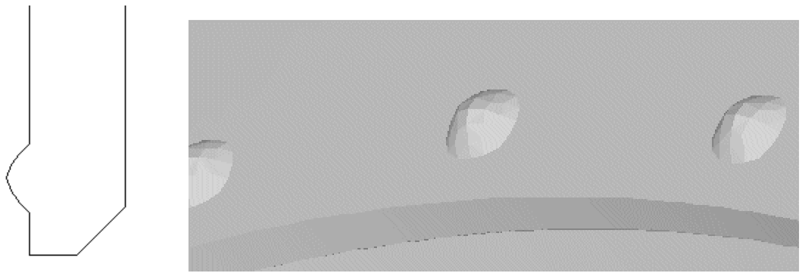
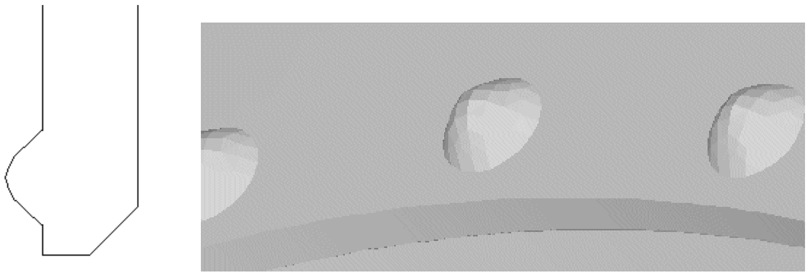


Figure 1 Geometry used in initial CFD simulations

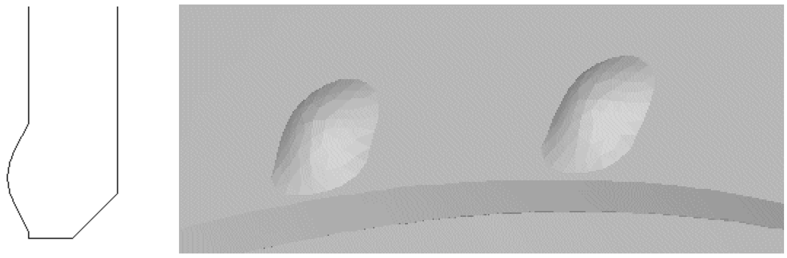
Four additional three-dimensional cases were run to mimic tests run by Advantica[1] in 300 mm pipe in which 32 grease spots were placed around the periphery of the orifice. This case was chosen because the grease distribution was fairly well defined and recorded at the beginning and end of the test. Figure 2 shows the distribution of contaminant, as defined in the simulations. Case 2 represented the grease spot distribution at the start of the test. Cases 3 and 4 were intended to approximate the shape of the grease spots as they were smeared across the plate during the test. Case 1 was included to assess the sensitivity of the discharge coefficient to smaller grease spots.



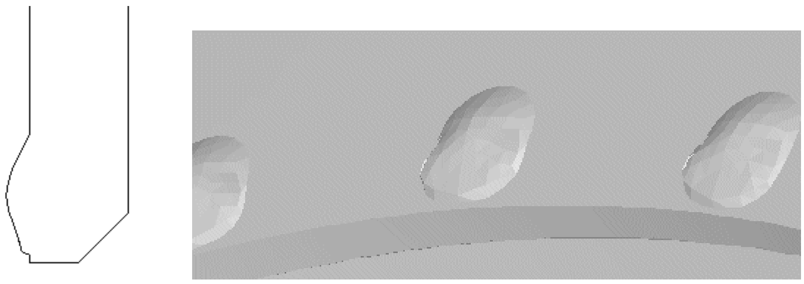
a) Case 1, spot height = 2 mm



b) Case 2, spot height = 2.5 mm



c) Case 3, spot height = 2mm

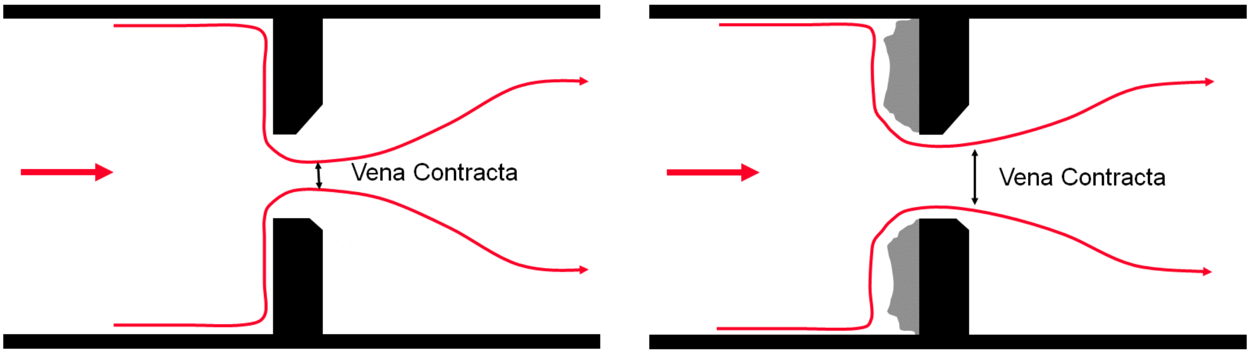


d) Case 4, spot height = 2mm

Figure 2 Grease spot simulations

In all cases the contaminant was represented as a smooth static wall. Turbulence effects were represented using the realisable k-ε turbulence model[4].

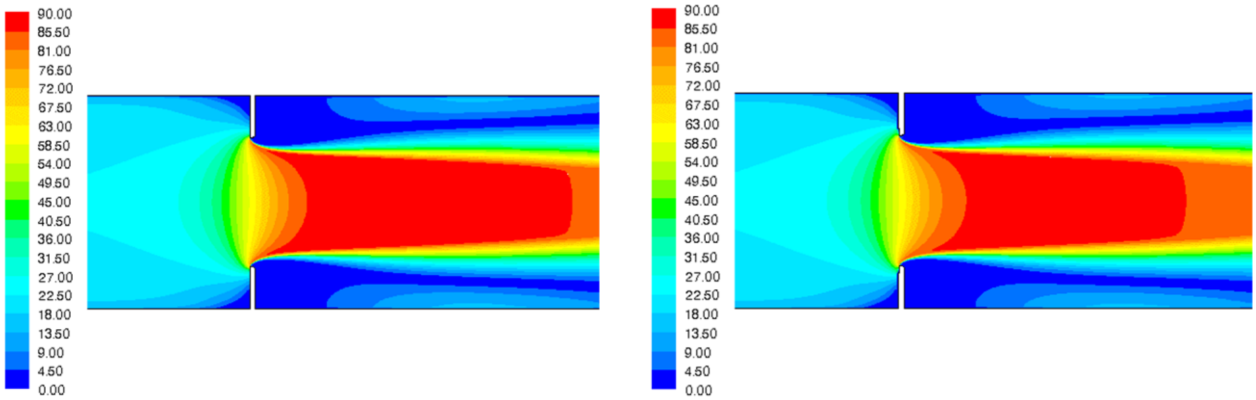
Figure 3 illustrates the typical flow behaviour observed in the CFD simulations. For a clean plate (Figure 3a) flow accelerates radially inwards along the front face until it reaches the edge of the orifice where it separates to form a Vena Contracta. This Vena Contracta defines the minimum flow area through the orifice plate and hence controls the measured pressure difference across the plate. When the front face of the plate is contaminated (Figure 3b) flow separates from the front face of the plate at a slight angle, increasing the size of the Vena Contracta, reducing the pressure difference across the plate and resulting in a negative flow measurement error and an increase in the discharge coefficient C.



a) Clean Plate *b) Contaminated Plate*

Figure 3 Illustration of the effect of contamination on flow through an orifice plate

This behaviour can be seen in the CFD predictions. In Figure 4 the red, high velocity contour is more extensive for the clean plate simulation because higher velocities occur in the Vena Contracta.



a) Clean plate *b) Contaminated Plate*

Figure 4 Predicted velocity contours (m/s) for a clean and a contaminated plate

The CFD results are summarised in Table 1.

The initial source of test data on contaminated orifice plates is the work performed by Advantica[1, 2] in 300 mm pipe. Data in ISO/TR 12767[5] suggest that shifts in discharge coefficient of up to +5.15% can be expected when grease extends across the full face of the orifice. When a 10 mm ring of grease is cleaned from the edge of the orifice shifts of between +0.61% and +1.00 % occur. For a 20 mm ring shifts of between +0.50% and +0.60% occur. These results are generally consistent with the CFD predictions. However, these data relate to tests in which the contaminant grease moved, making like-for-like comparison with these CFD predictions difficult.

Table 1. Summary of CFD Simulation Results

β	Re_D	*r* (mm)	*h* (mm)	*C*	% shift in *C*
0.6	1.0E+07	0	0	0.59814	0
0.6	1.0E+07	0	1.2	0.59812	-0.003
0.6	1.0E+07	2	1.2	0.63948	6.911
0.6	1.0E+07	4.5	1.2	0.61107	2.161
0.6	1.0E+07	10	1.2	0.60133	0.533
0.6	1.0E+07	20	1.2	0.59873	0.099
0.6	1.0E+07	2	1.54	0.65850	10.092
0.6	1.0E+07	4.5	1.54	0.61709	3.168
0.6	1.0E+07	10	1.54	0.60259	0.745
0.6	1.0E+07	20	1.54	0.59896	0.137
0.6	1.0E+07	4.5	2.59	0.64354	7.590
0.6	1.0E+07	10	2.59	0.60773	1.604
0.6	1.0E+07	20	2.59	0.59985	0.286
0.6	1.0E+06	0	0	0.60237	0
0.6	1.0E+06	10	1.2	0.60543	0.509
0.6	1.0E+06	20	1.2	0.60290	0.089
0.6	1.0E+07	0	0	0.59959	0
0.6	1.0E+07	grease spot case 1		0.60071	0.188
0.6	1.0E+07	grease spot case 2		0.60292	0.556
0.6	1.0E+07	grease spot case 3		0.60487	0.881
0.6	1.0E+07	grease spot case 4		0.60724	1.277
0.2	1.0E+07	0	0	0.59278	0
0.2	1.0E+07	2	1.2	0.66921	12.894
0.2	1.0E+07	3.3	1.2	0.62153	4.850
0.2	1.0E+07	5.2	1.2	0.60554	2.153
0.2	1.0E+07	10	1.2	0.59692	0.698
0.2	1.0E+07	20	1.2	0.59353	0.127
0.4	1.0E+07	0	0	0.59743	0
0.4	1.0E+07	2	1.2	0.64356	7.723
0.4	1.0E+07	4.5	1.2	0.61150	2.355
0.4	1.0E+07	10	1.2	0.60128	0.644
0.4	1.0E+07	20	1.2	0.59766	0.039
0.75	1.0E+07	0	0	0.58750	0.000
0.75	1.0E+07	2	1.2	0.62609	6.569
0.75	1.0E+07	4.5	1.2	0.59875	1.915
0.75	1.0E+07	10	1.2	0.58949	0.338
0.75	1.0E+07	20	1.2	0.58753	0.006

Figure 5 shows that the grease spot simulations for cases 2 to 4, which correspond to the Advantica tests, predicted shifts in C over a +0.556% to +1.277% range. This compares with a range of +0.6 to +1.3% seen in the Advantica tests for similar contaminant distributions.

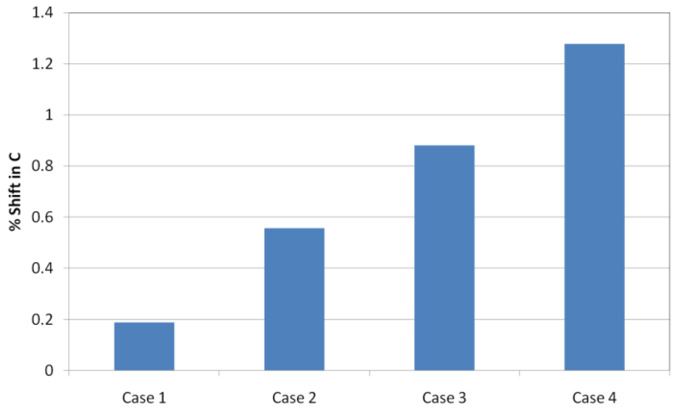


Figure 5 Predicted shift in discharge coefficient from grease spot simulations

A contamination angle, θ, was defined thus:

$$\theta = \tan^{-1}\left(\frac{h}{r}\right)$$

In Figure 6 the CFD predictions are plotted against the contaminant angle. It can be seen that the $\beta = 0.6$ simulations almost lie on the same curve. The $\beta = 0.2$ and $\beta = 0.4$ points lie above this curve and the $\beta = 0.75$ points lie below the curve.

In the grease spot tests the spots covered approximately 35.2% of the circumference around the orifice plate edge. When the grease spot discharge coefficient shift predictions are multiplied by 2.84 (2.84 = 1/0.352) these points lie on the same line as the other $\beta = 0.6$ predictions.

In Figure 6 the Advantica data (with a clean ring) in ISO/TR 12767 are shown for comparison.

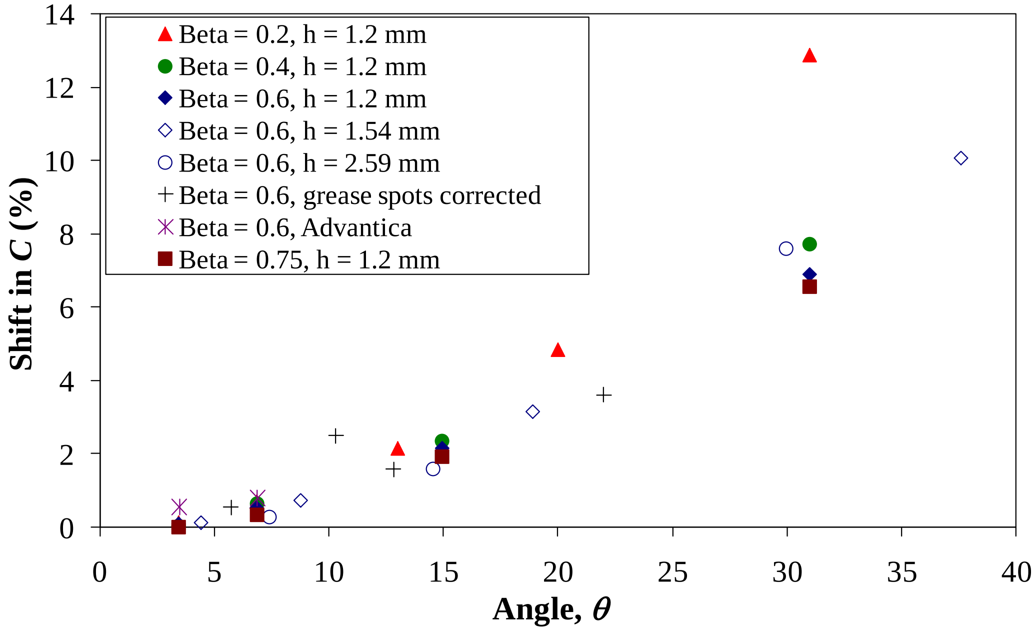


Figure 6 Shift in discharge coefficient for various contaminant angles (θ), all in 12" (300 mm) pipe: CFD results and Advantica experimental data

3 Experimental work

To verify and to refine the model a 4-inch orifice run of internal diameter 102.26 mm and three orifice plates of diameter ratios 0.4, 0.6 and 0.75 with spark-eroded orifices were manufactured. Discs of 0.5 and 1 mm thickness (h) were manufactured whose OD was 98 mm. The ID of each disc, d_i, is given in Table 2. r is the width of the plate between the orifice edge and the disc. The OD and ID were produced by spark erosion. They were carefully centred and glued to the orifice plates. The orifice plates were calibrated both with no added disc (as a baseline) and with an added disc. The tests were carried out in nitrogen in the TUV NEL high-pressure gas loop at a static pressure of 63 bar absolute. Both flange and corner tappings were used. The percentage change in discharge coefficient is given in Figures 7 – 12. The data are compared with the Reader-Harris/Gallagher (1998) Equation in ISO 5167-2:2003[6].

Mean deviations are given in Table 3 and Figures 13 and 14.

The new experimental data are then compared with the CFD and the Advantica data in Figure 15.

Table 2 Discs manufactured

Disc No	Disc Inside Diameter (mm)	Disc Thickness (mm)	Width of orifice plate between the orifice edge and the disc (mm)
	d_i	H	r
1	81.36	0.5	10 (β = 0.6) and 2.33 (β = 0.75)
2	81.36	1	10 (β = 0.6) and 2.33 (β = 0.75)
3	71.36	1	5 (β = 0.6)
4	71.36	0.5	5 (β = 0.6)
5	71.36	0.5	5 (β = 0.6)
6	71.36	1	5 (β = 0.6)
7	60.90	0.5	10 (β = 0.4)
8	60.90	1	10 (β = 0.4)
9	50.90	1	5 (β = 0.4)
10	96.70	0.5	10 (β = 0.75)
11	96.70	1	10 (β = 0.75)
12	86.70	1	5 (β = 0.75)
13	66.36	0.5	2.5 (β = 0.6)
14	66.36	1.0	2.5 (β = 0.6)
15	76.36	1.0	7.5 (β = 0.6)
16	45.90	0.5	2.5 (β = 0.4)
17	45.90	1.0	2.5 (β = 0.4)
18	50.90	0.5	5 (β = 0.4)

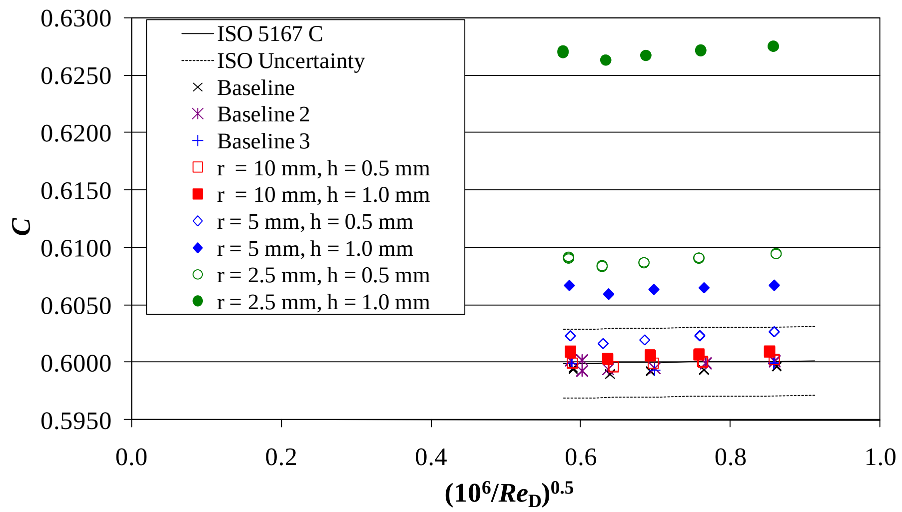


Figure 7 The effect of contamination: β = 0.4; flange tappings

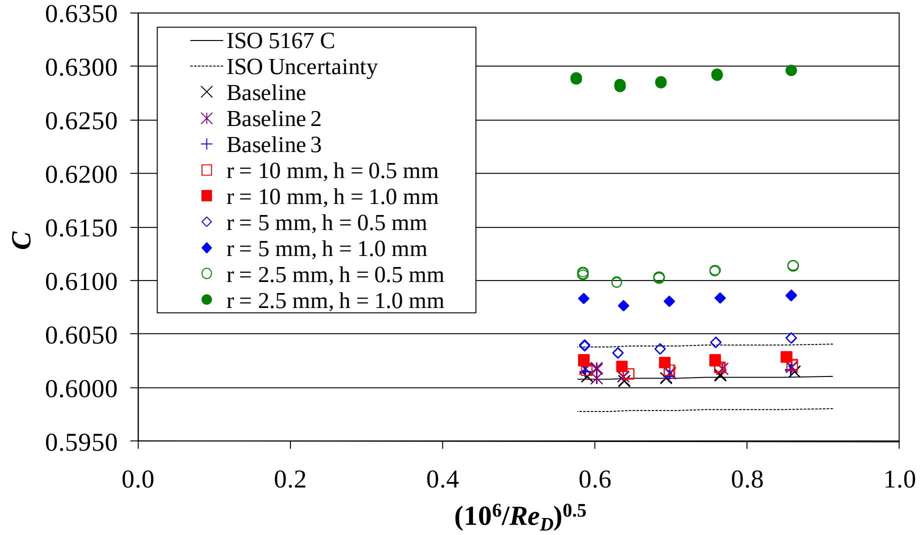


Figure 8 The effect of contamination: β = 0.4; corner tappings

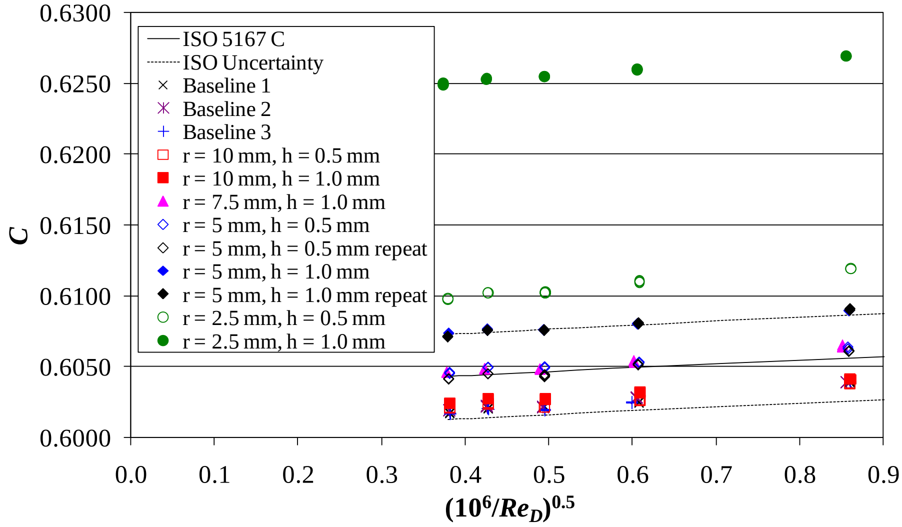


Figure 9 The effect of contamination: β = 0.6; flange tappings

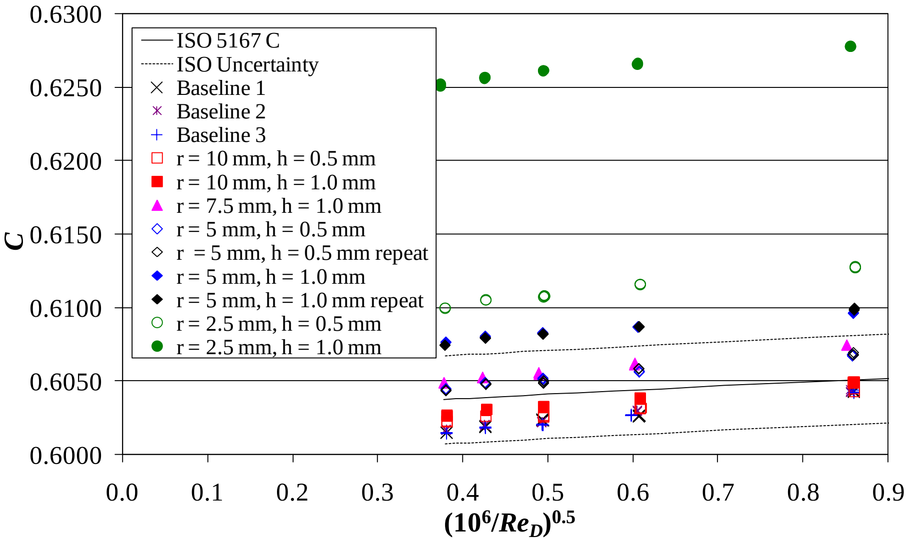


Figure 10 The effect of contamination: β = 0.6; corner tappings

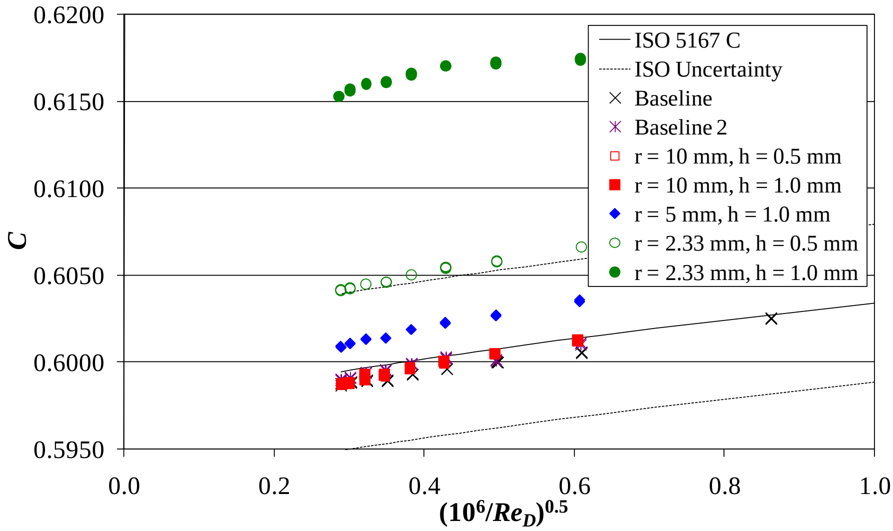


Figure 11 The effect of contamination: β = 0.75; flange tappings

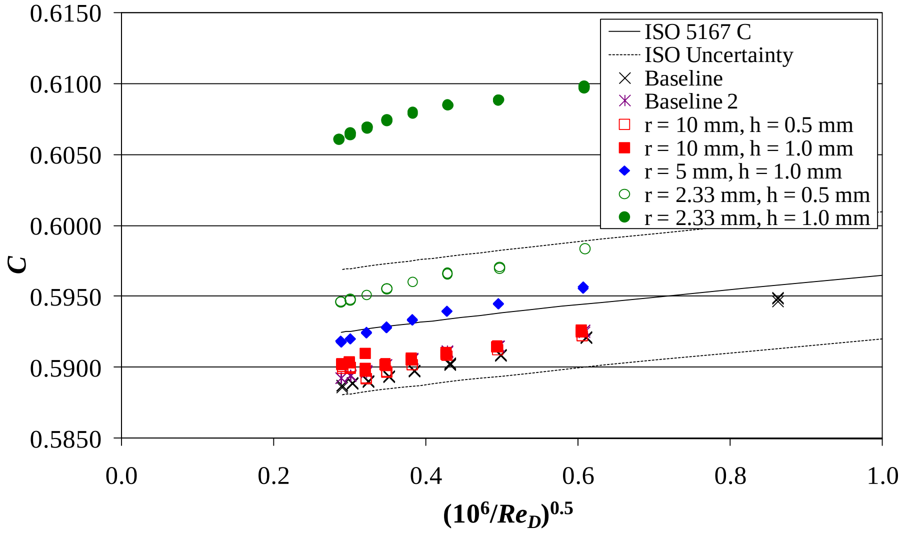


Figure 12 The effect of contamination: β = 0.75; corner tappings

Table 3 The effect of contamination: experiment: mean deviations

β	*h*	*r*	% change in *C*	
	mm	mm	Flange	Corner
0.4	0.5	10	0.072	0.075
0.4	1	10	0.190	0.204
0.4	0.5	5	0.442	0.452
0.4	1	5	1.143	1.154
0.4	0.5	2.5	1.575	1.562
0.4	1	2.5	4.582	4.609
0.6	0.5	10	0.018	0.071
0.6	1	10	0.092	0.163
0.6	1	7.5	0.455	0.545
0.6	0.5	5	0.421	0.462
0.6	1	5	0.900	0.977
0.6	0.5	2.5	1.351	1.419
0.6	1	2.5	3.866	3.943
0.75	0.5	10	0.017	0.010
0.75	1	10	0.018	0.070
0.75	1	5	0.387	0.554
0.75	0.5	2.33	0.916	1.001
0.75	1	2.33	2.814	3.000

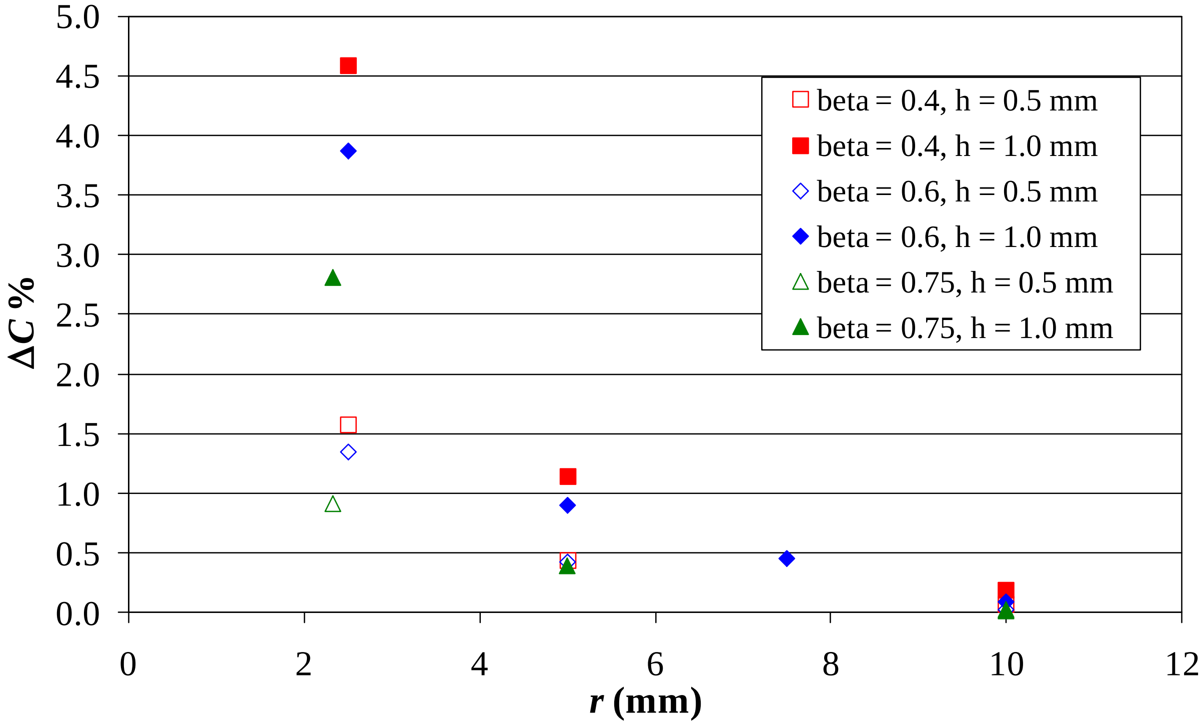


Figure 13 The effect of contamination: flange tappings

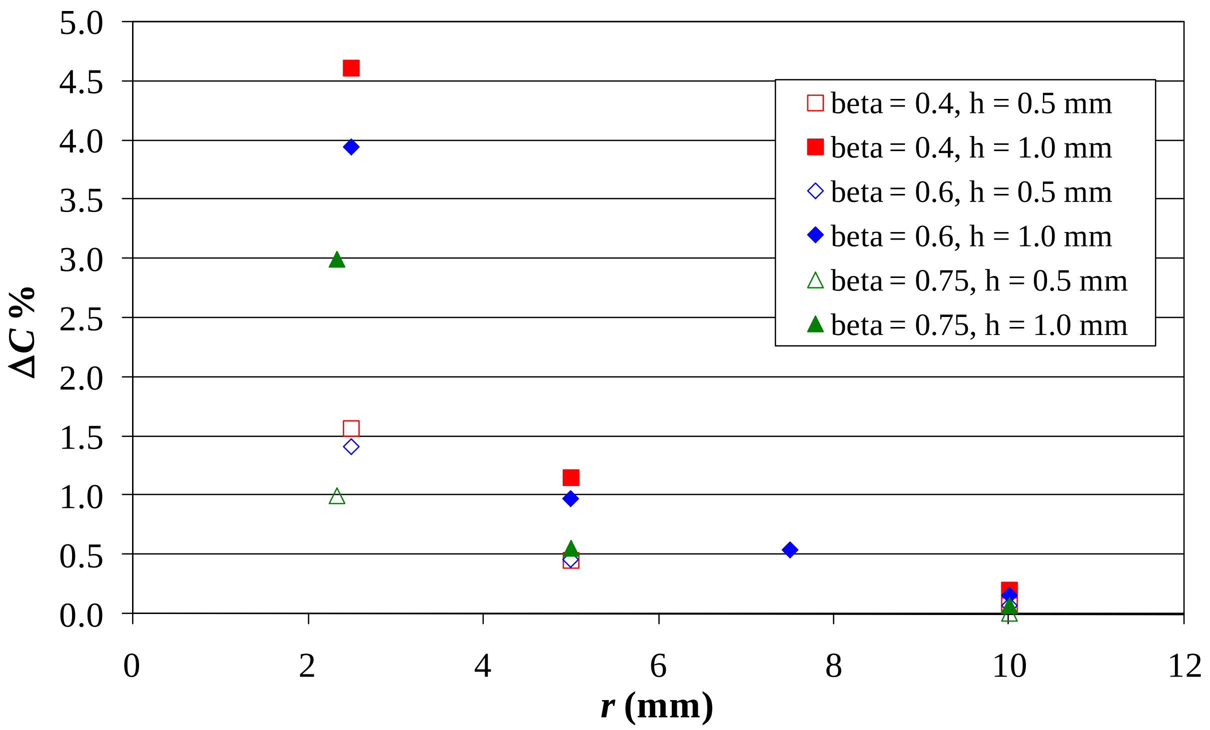


Figure 14 The effect of contamination: corner tappings

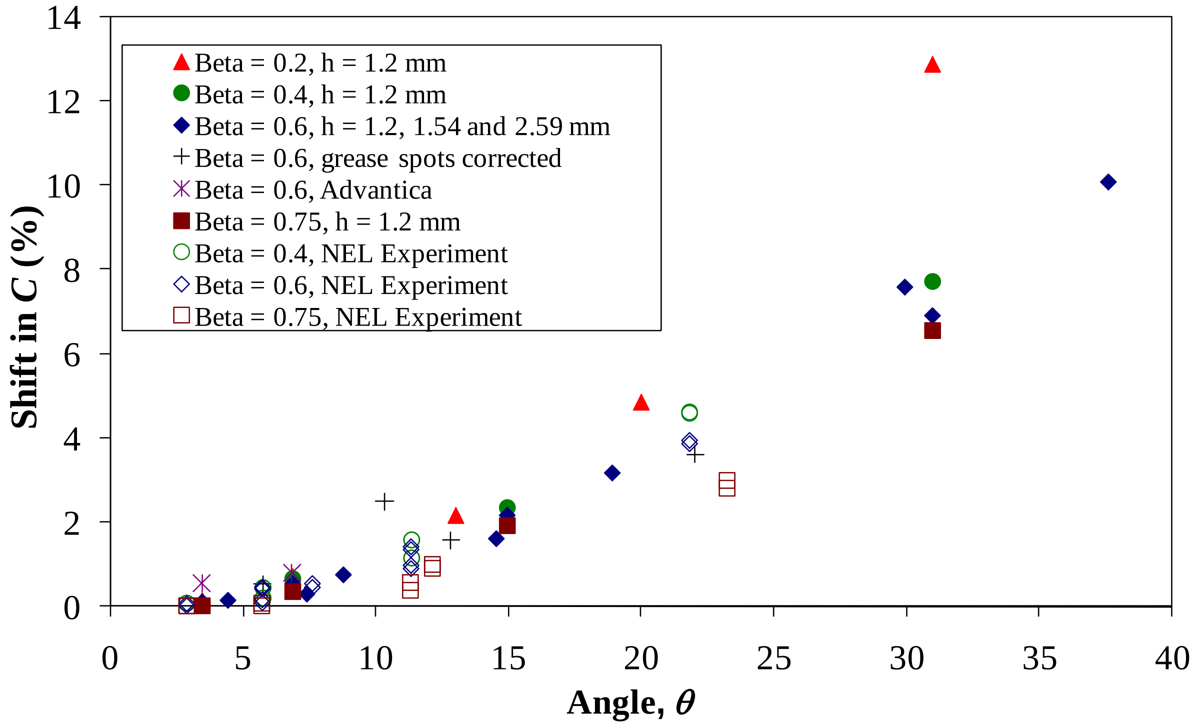


Figure 15 Shift in discharge coefficient for various contaminant angles (θ): CFD and Advantica data as in Figure 6 (12” (300 mm) pipe); NEL experiment 4” (100 mm) pipe

4 Analysis

It is clear from the experimental data, as indeed from the CFD, that although h/r is the most important effect on the shift it is not the only effect. For a given h/r the shift is smaller for larger β and for larger r. It was not at first obvious what the correct model should be: terms in h/d or r/d were tried without success. The ratio of r to the dam height proved to be satisfactory, and so the following form for S, the percentage shift in the discharge coefficient, was tried:

$$S = a\left(\frac{h}{r}\right)^{m}\left(1-\frac{2r}{D(1-\beta)}\right)^{n}$$

The best fit of this form to the experimental data was as follows:

$$S = 22.8\left(\frac{h}{r}\right)^{1.4}\left(1-\frac{2r}{D(1-\beta)}\right)^{4}$$

This has an uncertainty of 0.28 % based on 2 standard deviations. It is possible to include an additional term based on tapping location, but there is insufficient evidence to produce its exact form, and further data in different pipe sizes would be required to derive it. Its effect on the uncertainty is very small. There are other minor improvements to the equation that are possible, but there are insufficient data to justify too complicated a form.

This equation can then be compared with the CFD calculations. If only data for which $h/r < 0.4$ are considered (similar to the range of the experiments), their r.m.s. deviation from the equation is 0.24%. In fact the CFD-calculated values require a smaller value of a than the experimental data, and if 22.8 were replaced by 20.3 (a reduction of only 11%) the r.m.s. deviation from the equation for these data would be 0.14%. The CFD are in remarkably good agreement with the experiments and support the inclusion of the new model in a revision of ISO/TR 12767[5].

5 Conclusions

Contamination to orifice plates was simulated by sticking circular metal discs of defined thickness and radius to the plates so as to leave an untouched region in the neighbourhood of the sharp edge. This simulates the cleaned region often observed on contaminated plates. The effect of this contamination has been measured in nitrogen at 63 bar absolute and an equation for the effect of this contamination determined with an uncertainty of 0.28 %. The effect of contamination has also been calculated using CFD, and good agreement between CFD and experiment obtained.

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