THE COMPLIANCE TEST FOR FLOW CONDITIONERS AS APPLIED TO A ZANKER FLOW CONDITIONER PLATE WITH A VENTURI TUBE

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Summary

This paper describes the test work undertaken to establish that the compliance test in ISO 5167-1:2003 is satisfactory for Venturi tubes and also to determine the required upstream lengths when a Zanker Flow Conditioner Plate is installed upstream of a Venturi tube. In essence the Zanker Flow Conditioner Plate met the compliance test upstream of a Venturi tube provided that there is at least $3D$ between the plate and the upstream pressure tapping of the Venturi tube and $7D$ between the plate and any upstream fitting. However, if the compliance test were to apply to flow conditioners with Venturi tubes at high Reynolds number, it is worth noting that the shift in discharge coefficient due to a flow conditioner does not have a single value for all $Re_D > 3 \times 10^6$. Moreover, the requirements of the compliance test in terms of range of friction factor may be too restrictive.

Notation

C	Discharge coefficient	-
ΔC	Shift in discharge coefficient	-
D	Diameter of entrance cylinder	m
d	Diameter of Venturi throat	m
d_{tap}	Tapping hole diameter	m
k	Pipe roughness (as on the Moody diagram)	m
Q	Volumetric flowrate	m^3/s
R_a	Arithmetical mean deviation of the roughness profile	m
Re_D	Pipe Reynolds number $\left(= \dfrac{4Q}{\pi D \nu} \right)$	-
Re_d	Throat Reynolds number ($=Re_D/\beta$)	-
Re^*	Venturi throat tapping Reynolds number ($= Re_d d_{tap}/d$)	-
β	Diameter ratio ($= d/D$)	-
λ	Friction factor	-
ν	Kinematic viscosity	m^2/s

Introduction

Differential pressure flowmeters are affected by upstream installation. They require a significant upstream straight length, and one way of reducing the required upstream straight length is to use a flow conditioner. Although ISO 5167-1:1991 [1] did not encourage the use of flow conditioners to a great extent the revised version does: see ISO 5167-1: 2003 [2] and ISO 5167-2: 2003 [3] (unpublished at the time of writing). Work has been done using orifice plates to establish that the compliance test for flow conditioners in ISO 5167-1:2003, described in the next section, is

reasonable. This report describes the test work undertaken to establish that the compliance test in ISO 5167-1:2003 is satisfactory for Venturi tubes and also to determine the required upstream lengths when a Zanker Flow Conditioner Plate is installed upstream of a Venturi tube.

The compliance test

Instead of requiring the use of particular flow conditioners ISO 5167-1: 2003 contains a compliance test so that if a flow conditioner provides sufficiently small shifts in discharge coefficient downstream of certain major flow disturbers then it can be used with the same type of primary device downstream of any upstream fitting. Once the compliance test described below has been met the flow conditioner can be used with a primary device with any value of β up to 0.67 without increasing the uncertainty of the discharge coefficient to take account of the installation. Additional test work not described here is required if β is to exceed 0.67. The ranges of distances, expressed in terms of numbers of pipe diameters, between the flow conditioner and the primary device and between the upstream fitting and the flow conditioner which are used in the tests determine the acceptable ranges of distances when the flowmeter is used. Most of the test work is undertaken for β = 0.67 on the basis that if a flow conditioner performs successfully for β = 0.67 it will perform successfully for smaller β. This is certainly true in non-swirling flow. However this is not necessarily true for high swirl; so the test in high swirl is also performed for β = 0.4, as, for an orifice plate at any rate, the effect of high swirl is greater for β = 0.4 than for β = 0.67.

The main requirements of the compliance test are as follows: using a primary device of β = 0.67 the shift in discharge coefficient from that obtained in a long straight pipe must be less than 0.23 per cent when the flow conditioner is installed in each of the following situations:

a) In good flow conditions

b) Downstream of a 50 per cent closed gate valve (or a D shaped orifice plate)

c) Downstream of a device producing high swirl (the device should produce a maximum swirl angle across the pipe of at least 24° at a distance 18D downstream of it or at least 20° at a distance 30D downstream of it, where D is the pipe diameter).

These tests are required to establish that a flow conditioner does not have an adverse effect in good flow conditions, is effective in a highly asymmetric flow, and is effective in a highly swirling flow such as has been found downstream of a header.

Using a primary device of β = 0.4 the shift in discharge coefficient from that obtained in a long straight pipe must be less than 0.23 per cent when the flow conditioner is installed downstream of the same fitting as in c). This test is included in case there is still swirl downstream of the conditioner: the swirl may have more effect on the discharge coefficient for β = 0.4 than for β = 0.67.

To establish the acceptability of both the test facility and the primary devices with which the test is being conducted, the baseline discharge coefficients for each primary device, as measured in a long straight pipe by the test facility, must lie within the uncertainty limits of the discharge coefficient equation for an uncalibrated primary device as given in ISO 5167.

If the flow conditioner is to be acceptable at any pipe Reynolds number, Re_D, then it is necessary to establish that it not only meets the tests above for both β = 0.67 and 0.4 at one Reynolds number, but that it meets a) or b) or c) for β = 0.67 at a second Reynolds number. If the two pipe Reynolds numbers are Re_{low} and Re_{high} then they must meet the following criteria:

$$10^4 \leq Re_{low} \leq 10^6 \text{ and } Re_{high} \geq 10^6 \tag{1}$$

and

$$\lambda(Re_{low}) - \lambda(Re_{high}) \geq 0.0036, \tag{2}$$

where λ is the pipe friction factor [4], which may be obtained graphically from the Moody diagram or from the Colebrook-White equation

$$\frac{1}{\sqrt{\lambda}} = 1.74 - 2\log_{10}\left(\frac{2k}{D} + \frac{18.7}{Re_D\sqrt{\lambda}}\right) \tag{3}$$

with k evaluated as πR_a. The requirements on friction factor were determined in order that for an orifice plate the velocity profile will change sufficiently that the discharge coefficient changes by at least twice the maximum permitted shift in discharge coefficient due to installation. From [5] and [6] the effect of changes in friction factor on an orifice plate is given by

$$\Delta C = 3.134\beta^{3.5}\Delta\lambda. \tag{4}$$

Then taking C as 0.6, $\beta = 0.67$ and the minimum required change in C as 0.46 per cent gives equation (2).

If the flow conditioner is to be acceptable for any pipe size then it is necessary to establish that it not only meets the tests above for both $\beta = 0.67$ and 0.4 at one pipe size, but that it meets a) or b) or c) for $\beta = 0.67$ at a second pipe size. If the two pipe diameters are D_{small} and D_{large} then they must meet the following criteria:

$D_{small} \leq 110$ mm (nominal 4 inch) and $D_{large} \geq 190$ mm (nominal 8 inch).

Test work

The most satisfactory unpatented flow conditioner for use with an orifice plate appears to be a Zanker Flow Conditioner Plate [7]. This flow conditioner was therefore chosen for the test work to provide both a reduction in required straight lengths upstream of a Venturi tube and a proof that the compliance test in ISO 5167-1:2003 is reasonable with other meters besides orifice plates.

No Venturi tube with $\beta = 0.67$ was available; so one with $\beta = 0.65$ was used. It had a standard convergent angle of 21° and a divergent angle of 7½°. It had a machined convergent, and was manufactured from stainless steel. Three pairs of tappings were available, A-A, C-C, and D-D. The Venturi tube had four pairs of equi-spaced tappings, but B-B were blocked. All the tappings were 4 mm in diameter. The upstream tappings in each case were of constant diameter for a length of 53 mm. As originally manufactured the throat tappings were of constant diameter for a length of 94 mm; however, before this project started the C and D throat tappings had been modified by redrilling the tappings from the outside with a 9 mm drill so that for the C tapping the remaining length of 4 mm tapping was 20 mm (expanding at that point to a diameter of 9 mm) and for the D tapping the remaining length of 4 mm tapping was 10 mm. The A throat tapping had not been modified.

Baselines were run and are given in Figure 1. Upstream of the upstream tappings of the Venturi tube there was 45D of machined pipe of diameter very close to that of the upstream cylinder of the Venturi tube preceded by 37D of pipe of Schedule 10 preceded by a tube bundle flow

conditioner. Examination of these data and other data collected with the same Venturi tube suggest that the data for $Re_D < 3.5 \times 10^5$ are more scattered and less linear than those above that Reynolds number, and so only data for $Re_D > 3.5 \times 10^5$ are used in the subsequent analysis. All the fitted lines are within the range of discharge coefficient expected by ISO 5167-1.
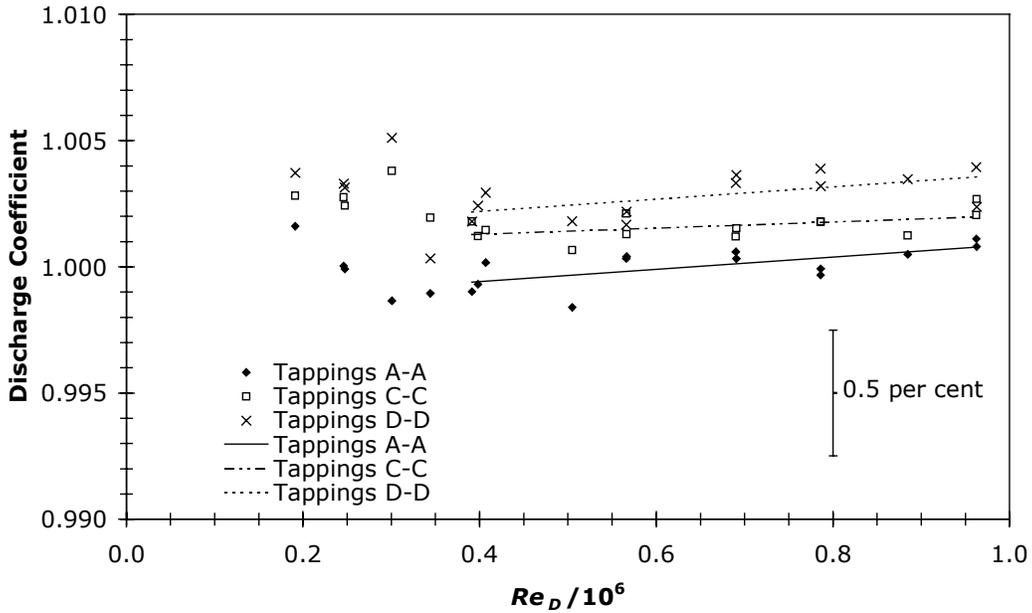

Figure 1. Baseline data for $\beta = 0.65$ Venturi tube

The Zanker Flow Conditioner Plate was installed in good flow conditions $1D$, $3D$ and $7D$ upstream of the Venturi tube. All distances upstream of the Venturi tube are measured from the plane of the upstream pressure tappings. To illustrate the method of analysis the data collected with Tappings A-A with a Zanker Flow Conditioner Plate $1D$ upstream of the Venturi tube are shown in Figure 2. The mean value of $Re_D/10^6$ for this installation is 0.6579 and is marked on the figure; this value gives the minimum uncertainty for that line. The difference between the fitted line for the installation at this value of $Re_D/10^6$ and the baseline is evaluated for each pair of tappings and considered to be the shift for this installation. This difference is marked on Figure 2.
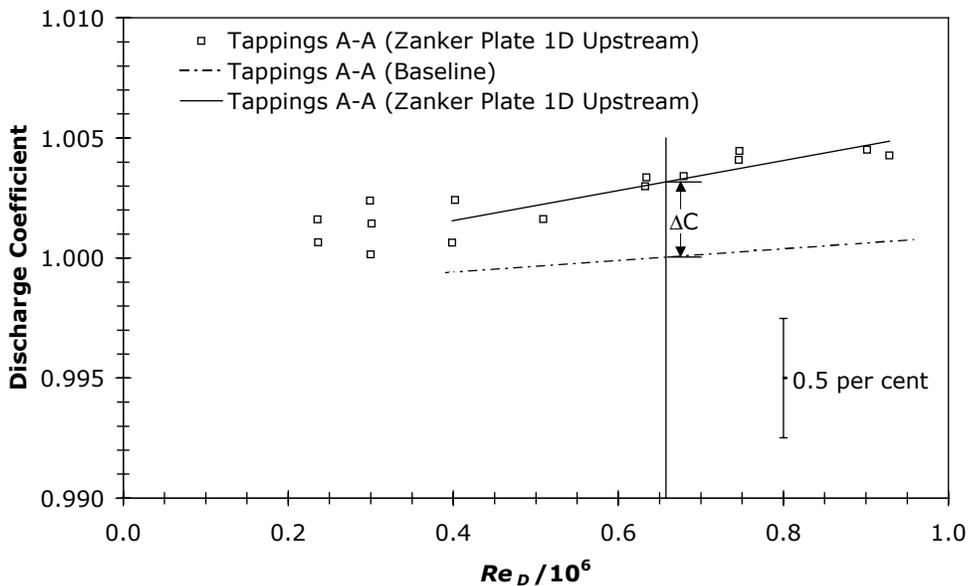

Figure 2. Data with Zanker Flow Conditioner Plate 1D upstream of $\beta = 0.65$ Venturi tube
(100 mm (4-inch), water) in good flow conditions

The calculated shifts in discharge coefficient for the Zanker Flow Conditioner Plate in good flow conditions over a range of distances from the Venturi tube are given in Figure 3.
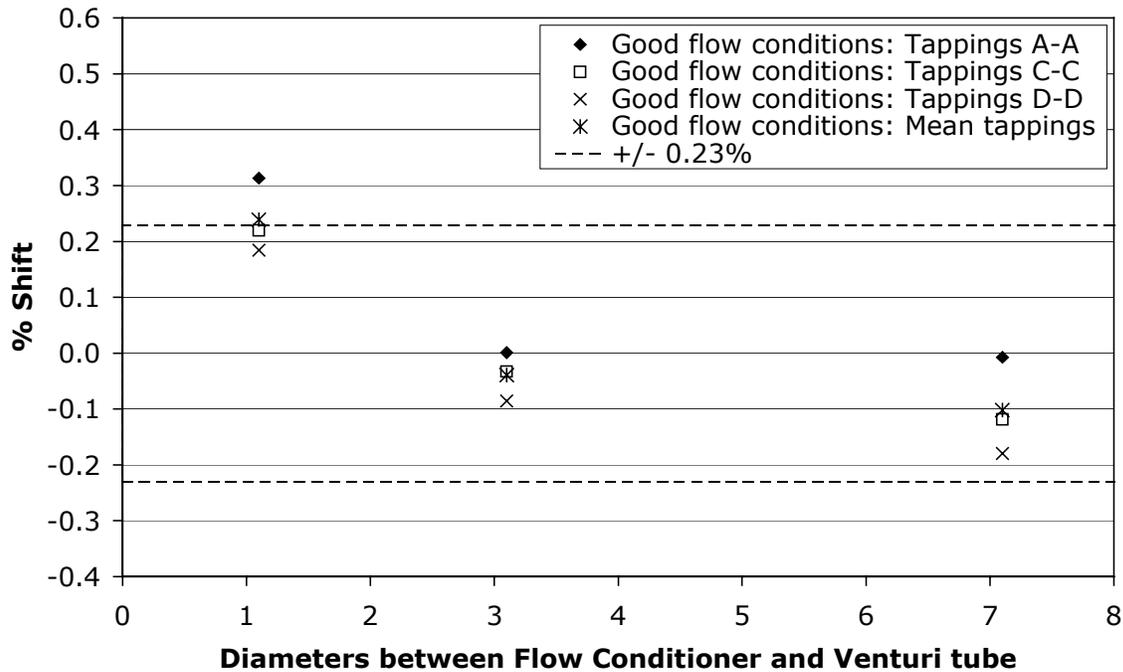

Figure 3. Effect of a Zanker Flow Conditioner Plate upstream of a Venturi tube
(100 mm (4-inch) β = 0.65, water) in good flow conditions

It was then necessary to collect additional data with a Zanker Flow Conditioner Plate upstream of the Venturi tube of β = 0.65 in disturbed flow conditions. Two upstream flow disturbers were used, a D-shaped plate and a swirl generator. The D-shaped plate was of thickness 3 mm with a 1.5 mm chamfer on its downstream face. The swirl generator used in the project had 8 blades angled at 27.5° to the flow with a central hub. The requirement in ISO 5167-1: 2003 is that it should produce a maximum swirl angle across the pipe of at least 24° at a location 18D downstream of it. It was therefore set up with a pitot traverse section 18D downstream of it. Several traverses were made. The pitot tube caused a constant blockage. The pipe Reynolds number was approximately 3.3 × 10^5. The perpendicular traverses are referred to as AC and BD. A test was also carried out in a long straight pipe in which the differential pressure between the two side holes of the pitot tube was measured at several radial locations at an approximately constant flowrate as the angle of the pitot tube was varied: from a linear fit to these data the best estimate of the angular position of the pitot tube when the swirl was zero was determined. The swirl angles downstream of the swirl generator are then plotted in Figure 4. The maximum swirl angle was 28°. If the data were fitted assuming that the fluid is rotating like a solid body the swirl angle would be 26° on the wall. On the basis of the data here it is clear that the swirl generator met the requirement of ISO 5167-1: 2003.
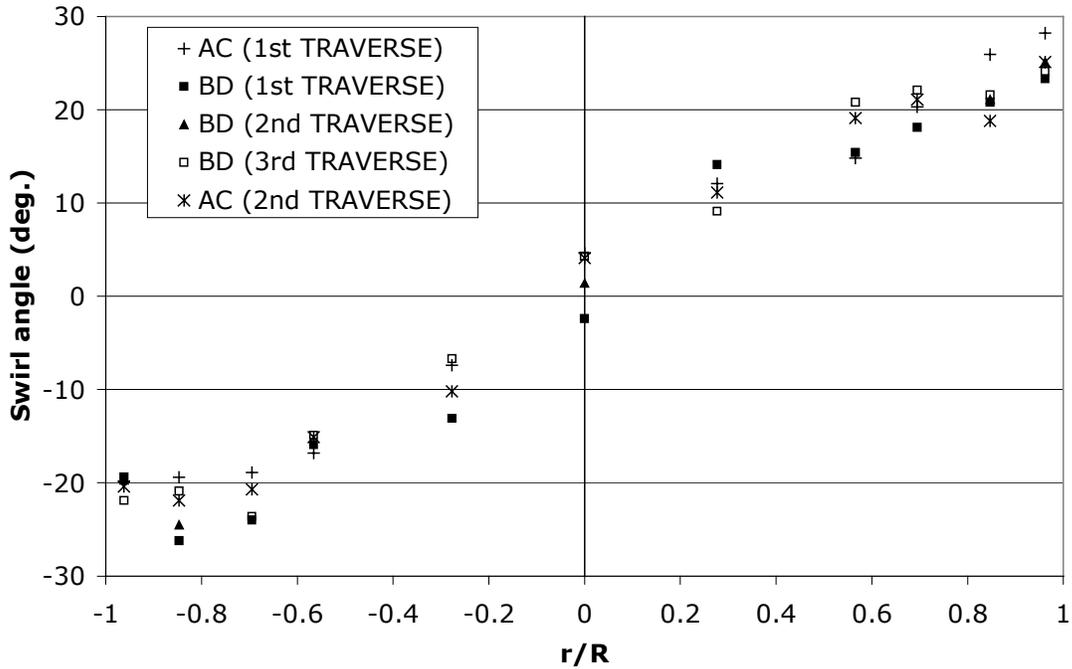
Figure 4. Swirl angles 18D downstream of the swirl generator

Tappings A-A were in the same angular position in the pipe as the middle of the circumference of the open portion of the D-shaped plate on the wall. For asymmetric flows it might be desirable to evaluate the mean shift by giving twice the weighting to the shift with tappings D-D in comparison with the shifts with tappings A-A and C-C, but this was not done: to do this would make very little difference to the mean. The calculated shifts in discharge coefficient when the Zanker Flow Conditioner Plate is installed 3*D* upstream of the upstream tappings of the Venturi tube are given in Figure 5. The data taken in good flow conditions are shown with the distance to the disturbance described as infinity.
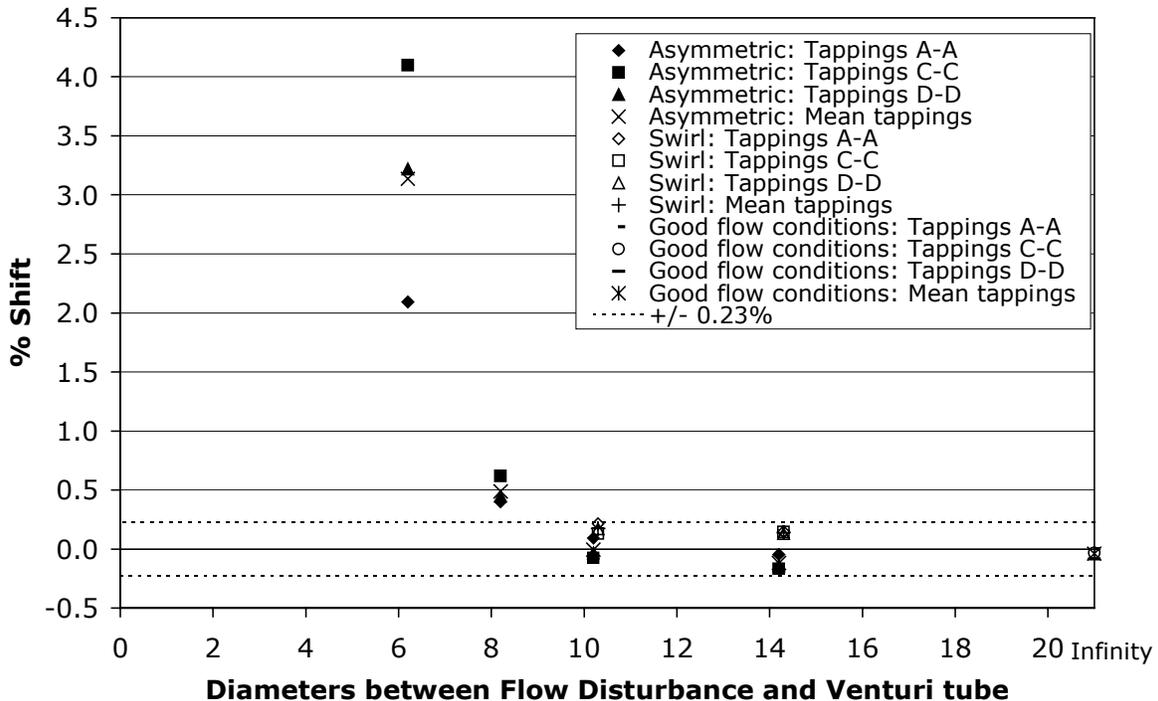

Figure 5. Effect of a Zanker Flow Conditioner Plate 3D upstream of a Venturi tube ($\beta = 0.65$)

It is striking how large the shift in discharge coefficient is when the D-shaped plate is too close to the Zanker Flow Conditioner Plate. It is necessary to have at least 7*D* between the D-shaped plate and the Zanker Flow Conditioner Plate. Because the vertical scale in Figure 5 has to be so large the data for which the distance between the flow disturbance and the Venturi tube is at least 8*D* are replotted in Figure 6.
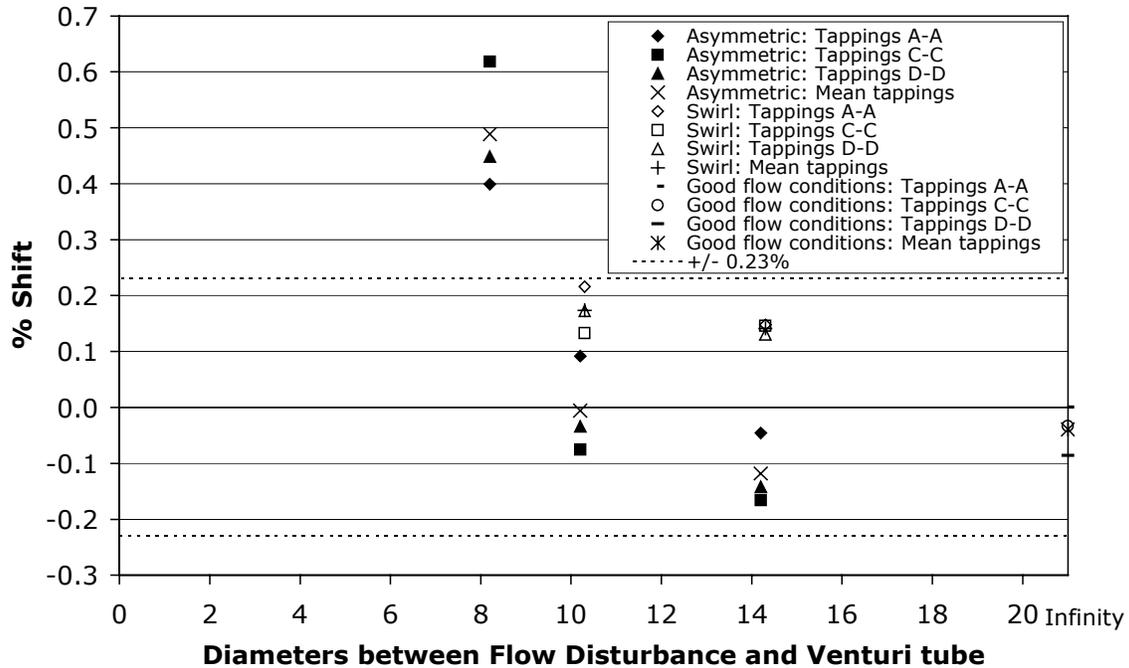

Figure 6. Effect of a Zanker Flow Conditioner Plate 3D upstream of a Venturi tube (β = 0.65)
when the distance between the flow disturbance and the Venturi tube is at least 8D.

Data were then taken when the Zanker Flow Conditioner Plate was 7*D* upstream of the upstream tappings of the Venturi tube and are given in Figure 7.
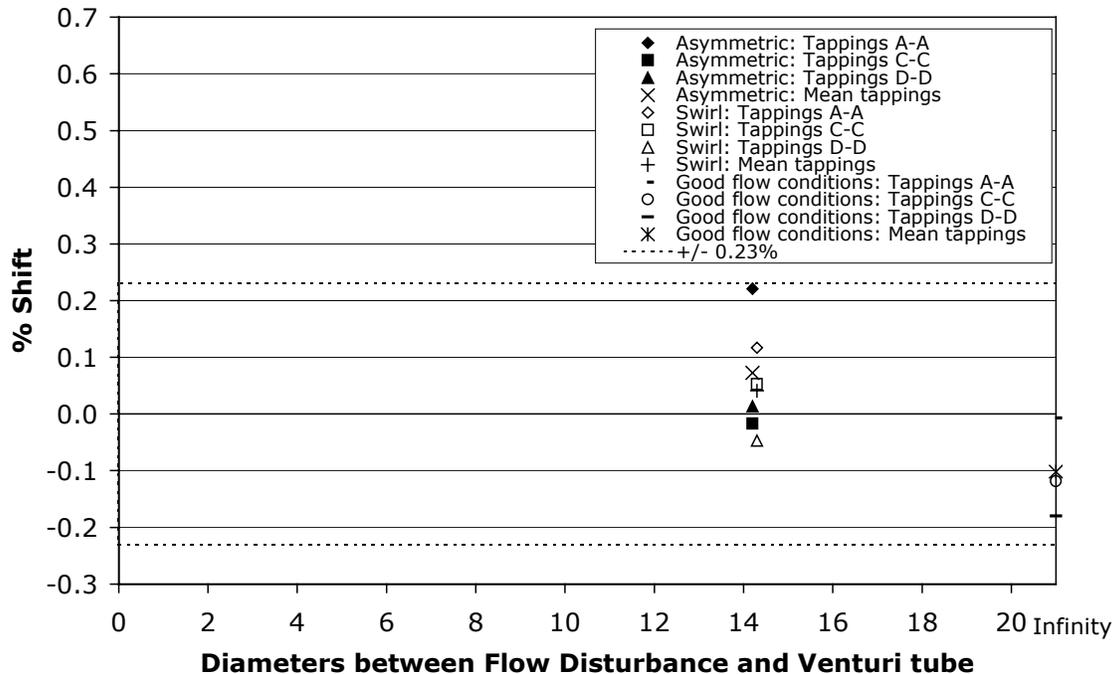

Figure 7. Effect of a Zanker Flow Conditioner Plate 7D upstream of a Venturi tube (β = 0.65)

It was then necessary to collect additional data with a Zanker Flow Conditioner Plate upstream of a Venturi tube of $\beta = 0.4$. The Venturi tube had four pairs of equi-spaced tappings, but only three pairs of tappings were used, A-A, C-C, and D-D. All the tappings were 4 mm in diameter. The upstream tappings in each case were of constant diameter for a length of 53 mm. The throat tappings in each case were of constant diameter for a length of 94 mm.

Examination of the data and other data collected with the same Venturi tube suggest that the data for $Re_D < 2 \times 10^5$ are more scattered and less linear than those above that Reynolds number, and so only data for $Re_D > 2 \times 10^5$ are used in the subsequent analysis. The calculated shifts in discharge coefficient when the Zanker Flow Conditioner Plate was installed upstream of a Venturi tube of $\beta = 0.4$ and downstream of the swirl generator are given in Figure 8.
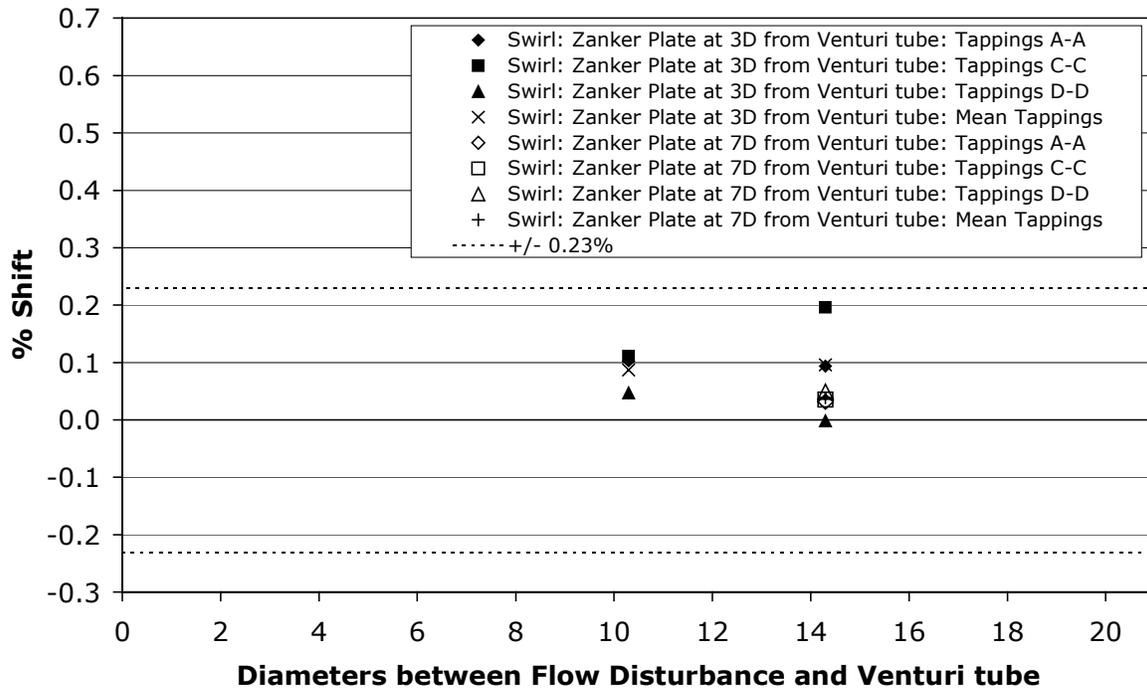

Figure 8. Effect of a Zanker Flow Conditioner Plate upstream of a Venturi tube ($\beta = 0.4$)

On the basis of the data collected above it can be seen that when the distance between the Zanker Flow Conditioner Plate and the Venturi tube exceeds 3D and that between an upstream flow disturbance and the Zanker Flow Conditioner Plate exceeds 7D the shift in discharge coefficient does not exceed 0.23 per cent for $\beta = 0.65$ and 0.4 in 100 mm (4-inch) pipe in water. It was then necessary to check that the same results hold in a larger size and at a higher Reynolds number.

Firstly data were collected in 200 mm (8-inch) Schedule 40 Venturi tubes. Here Venturi tubes with $\beta = 0.6$ and 0.75 were available. They had a standard convergent angle of 21° and a divergent angle of 7½°. They had machined convergents, and were manufactured from stainless steel. The Venturi tubes had four pairs of equi-spaced tappings, W-Z, X-Y, 5-1, and 8-3. All the tappings were 4 mm in diameter. The upstream tappings in each case were of constant diameter for a length of 53 mm. The throat tappings in each case were of constant diameter for a length of 94 mm. Upstream of the upstream tappings of the Venturi tube there was 10.7D of machined pipe of diameter very close to that of the upstream cylinder of the Venturi tube preceded by 21D of pipe of Schedule 40 preceded by 46D of pipe of Schedule 10 preceded by a tube bundle flow conditioner. The calculated shifts in discharge coefficient when the Zanker Flow Conditioner Plate is installed upstream of a 200 mm (8-inch) Venturi tube are given in Figure 9.
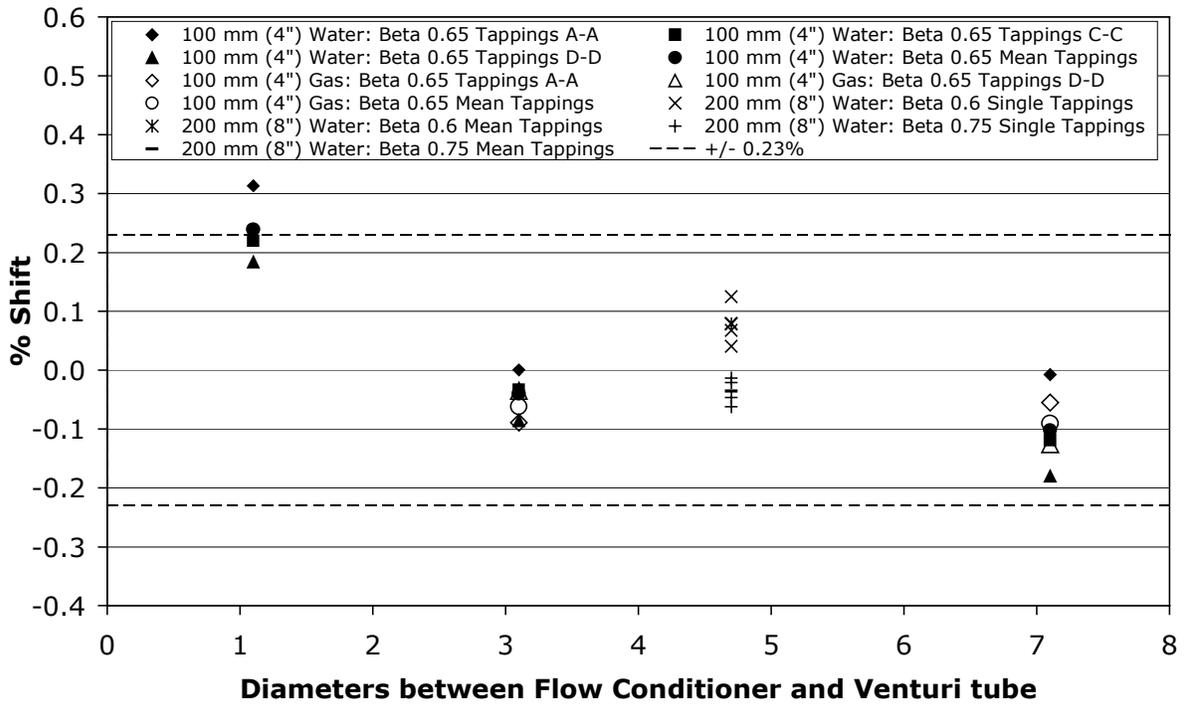
*Figure 9. Effect of a Zanker Flow Conditioner Plate upstream of a Venturi tube
in good flow conditions*

Secondly data were collected in high-pressure gas (nitrogen) in the same 100 mm (4-inch) β = 0.65 Schedule 40 Venturi tube as had been used in water. Only the A-A and D-D tappings were used. Data were collected in good flow conditions without a flow conditioner at static pressures of 20 barg and 40 barg. Data were also collected at a static pressure of 40 barg downstream of a Zanker Flow Conditioner Plate installed in good flow conditions 3*D* and 7*D* upstream of the upstream tappings of the Venturi tubes. The data for tapping pair A-A are presented in Figure 10.
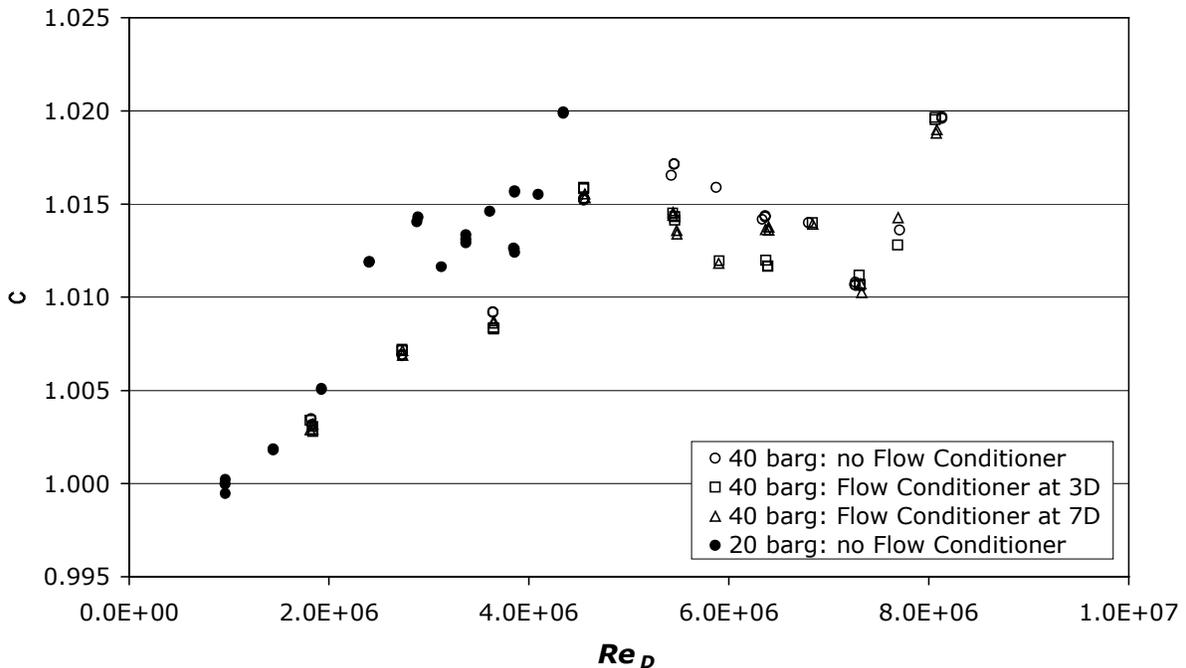

*Figure 10. Discharge coefficient of β = 0.65 Venturi tube (100 mm (4-inch), gas):
good flow conditions: tapping pair A-A*

Figure 10 shows that locating the Zanker Flow Conditioner Plate 3D or 7D upstream has virtually no effect on the discharge coefficient if $Re_D < 4.5 \times 10^6$ or $Re_D > 6.8 \times 10^6$ but for $5.5 \times 10^6 < Re_D < 6.4 \times 10^6$ shifts of approximately -0.3 per cent on average and -0.4 per cent at worst are achieved. A flow conditioner used with a Venturi tube over a range of high Reynolds numbers can give small shifts at some Reynolds numbers but larger shifts at others.

Much work has been undertaken at NEL [8, 9] to determine the best fit for the discharge coefficient for standard Venturi tubes and for those of different convergent angles. It has been observed that some of the variation in C can be removed by examining $C - C_{water}$ where C_{water} is the mean value for the water data for that Venturi tube. One cause for the change in discharge coefficient is static hole error [10], which is the effect that pressure tappings of finite size do not measure the pressure which would have been measured using an infinitely small hole. The effect of static hole error is that the measured pressure using a pressure tapping is higher than the static pressure would have been if the tapping had not been present. Since the effect at the upstream tapping is much smaller than the effect at the throat tapping it is possible simply to correlate the data with the throat tapping Reynolds number; the simplest presentation of this is to define the Venturi throat tapping Reynolds number

$$Re^* = \frac{d_{tap}}{d} Re_d \, ,\qquad\qquad(5)$$

where d_{tap} is the diameter of the throat tapping and Re_d is the throat Reynolds number, which is equal to Re_D/β.

It has been found that each set of data can be fitted as

$$C - C_{water} = a' - b' e^{-0.4(Re^*/10^5)} \, .\qquad\qquad(6)$$

Moreover it has been found desirable to examine water and gas data together to obtain an equation which fits all the data and to plot all the data against the exponential function of Re^* in Equation (6) rather than against Re^* itself. Figure 11 shows the data in Figure 10 together with the corresponding data taken in water replotted against $\exp(-0.4Re^*/10^5)$. The data are approximately linear. A line has been fitted to all the data without a flow conditioner. The standard deviation of all the data (including those taken with the Zanker Flow Conditioner Plate) about the line is almost the same as the standard deviation of the data without the flow conditioner about the line; so the presence of the Zanker Flow Conditioner Plate at 3D or 7D upstream of the Venturi tube would not significantly increase the uncertainty of the fitted line.
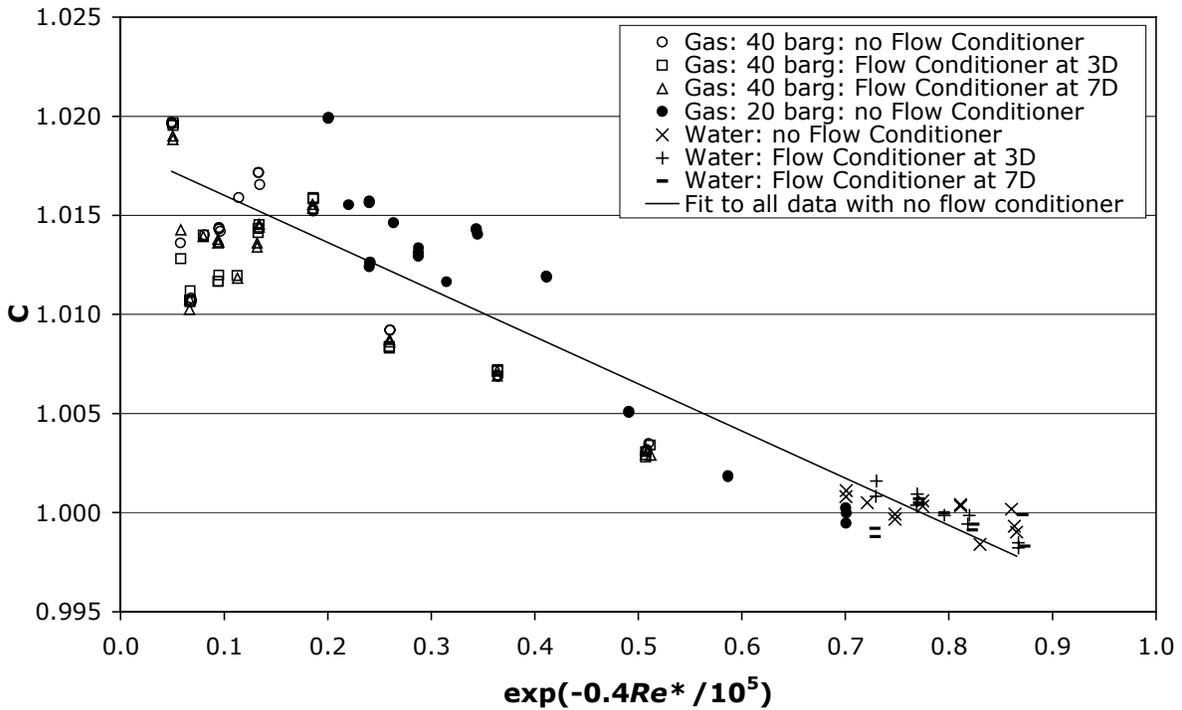
*Figure 11. Discharge coefficient of β = 0.65 Venturi tube (100 mm (4-inch), gas
and water from the same installations): good flow conditions: tapping pair A-A*

The data for tapping pair D-D from the same tests as those shown in Figure 10 are presented in
Figure 12. In Figure 10 and to a lesser extent in Figure 12 an effect of throat velocity on the
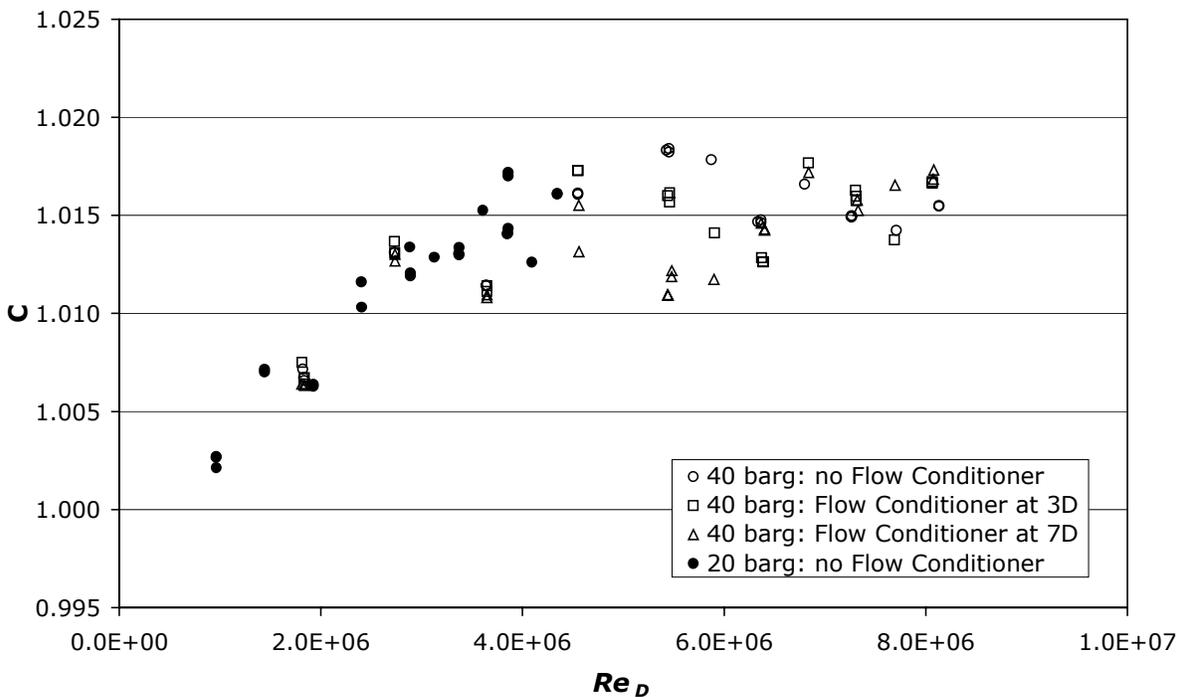discharge coefficient can be seen.

*Figure 12. Discharge coefficient of β = 0.65 Venturi tube (100 mm (4-inch), gas):
good flow conditions: tapping pair D-D*

Figure 12 shows that locating the Zanker Flow Conditioner Plate 3*D* or 7*D* upstream has virtually
no effect on the discharge coefficient if $Re_D < 3.6 \times 10^6$, but particularly for $4.5 \times 10^6 < Re_D <$

6.4×10^6 quite large shifts up to -0.7 per cent at worst are achieved. Figure 13 shows the data and the corresponding water data replotted against exp($-0.4Re*/10^5$).
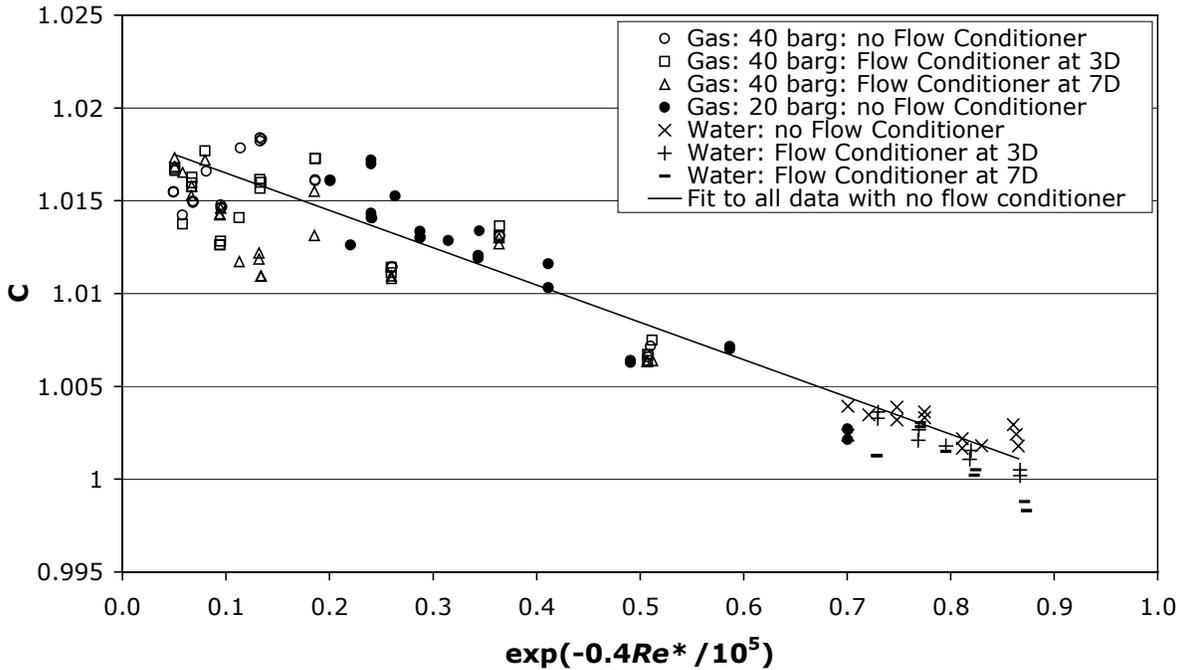

Figure 13. Discharge coefficient of β = 0.65 Venturi tube (100 mm (4-inch), gas and water from the same installations): good flow conditions: tapping pair D-D

For Tapping Pair D-D the agreement between data at 20 barg and those at 40 barg is much better than for tapping pair A-A, but the shifts due to the Flow Conditioner are larger. It is interesting that as exp($-0.4Re*/10^5$) tends to zero the difference between the fitted lines for the two tapping pairs also becomes small. The calculated shifts in discharge coefficient when the Zanker Flow Conditioner Plate is installed upstream of a 100 mm (4-inch) Venturi tube in high-pressure gas are given in Figure 9. These values were obtained by fitting lines to the 40 barg gas data as a function of exp($-0.4Re*/10^5$) in just the same way as lines were fitted to the water data (as a function of Re_D). Agreement with the shifts in water is very good.

In looking at possible Reynolds number effects within the compliance test it is necessary to look at the friction factor. The pipework upstream of the Venturi tube consists of several spool pieces, many of which have been honed. If it were assumed that they had roughness R_a = 1 μm then λ would be equal to 0.0136 when $Re_D = 5 \times 10^5$ and equal to 0.0106 when $Re_D = 4.5 \times 10^6$. So $\Delta\lambda$ = 0.0030. This just fails to meet the requirement in ISO 5167-1:2003. It does, however, meet the spirit of it in that C has changed by much more than 0.46 per cent between water and gas (and the flow conditioner still works). The test also meets the letter of the Standard in that there is no requirement for a high Reynolds number test with a Venturi tube as Venturi tubes cannot be used at high Reynolds number within the Standard. It would be easier to do the present test with an orifice plate as then $Re_D = 3 \times 10^5$ (λ = 0.0148) would be a reasonable value in water.

From the data presented above it can be seen that when there is at least $3D$ between the Zanker Flow Conditioner Plate and the Venturi tube and $7D$ between an upstream flow disturbance and the Zanker Flow Conditioner Plate the shift in discharge coefficient does not exceed 0.23 per cent for β = 0.65 and 0.4 in 100 mm (4-inch) pipe in water, and for β = 0.65 in 200 mm (8-inch) pipe in water, and for β = 0.65 in 100 mm (4-inch) pipe in high-pressure gas (provided that shifts between fitted lines are considered). On this basis the compliance test has been essentially

passed. Nevertheless at certain Reynolds numbers larger shifts may be achieved, and even in water the data for a Venturi tube are less linear than those for an orifice plate. The fact that β = 0.65 was used instead of β = 0.67 has only a small effect. It is encouraging that over the range of locations where the compliance test was passed the average of the shifts for all the 100 mm (4-inch) water data (with various upstream flow conditions) for β = 0.65 was 0.02 per cent. Over the range of locations where the compliance test was passed the average of the mean shifts for all the data in good flow conditions was -0.04 per cent. The smallness of these numbers suggests that bias is small. The fact that as much as 7D is required upstream of the Zanker Flow Conditioner Plate is a consequence of the interaction between the flow conditioner and the D-shaped plate. The minimum distance between a Zanker Flow Conditioner Plate and an orifice plate is 8.5D [3] if the compliance test is to be met.

Conclusions

Test work has been undertaken to determine the required upstream lengths when a Zanker Flow Conditioner Plate is installed upstream of a Venturi tube to meet the compliance test in ISO 5167-1:2003. In essence the Zanker Flow Conditioner Plate met the compliance test upstream of a Venturi tube provided that there was at least 3D between the plate and the upstream pressure tapping of the Venturi tube and 7D between the plate and any upstream fitting. The compliance test in ISO 5167-1:2003 is satisfactory for Venturi tubes. However, if the test were to apply to flow conditioners with Venturi tubes at high Reynolds number, it is worth noting that the shift in discharge coefficient due to a flow conditioner does not have a single value for all $Re_D > 3 \times 10^6$. Moreover, the requirements of the compliance test in terms of range of friction factor may be too restrictive.

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