34^{th} International North Sea Flow Measurement Workshop
25-28 October 2016

Technical Paper

Diagnostics and Orifice Plates: Experimental Work

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1 INTRODUCTION

Differential-pressure meters, including orifice plates, Venturi tubes and cone meters have been and remain the group of flowmeters most commonly used in industry. Orifice plates in particular provide the mainstay of gas fiscal metering systems worldwide. While ultrasonic meters have been installed in many installations in recent years, orifice plates continue to serve a useful function owing to their advantage of not requiring flow calibration and of having a dependence on the square root of density to provide mass flow (rather than the mass flow being directly proportional to the density).

One of the features of an ultrasonic flow meter is its ability to provide additional diagnostic information on the nature of the flow and the condition of the meter. This information can be used to check for the presence of additional uncertainty in the measured flow caused by, for example, swirl induced by upstream flow disturbances, a change in pipe roughness or damage to or degradation of the transducers. The ability to provide diagnostics is not limited to ultrasonic meters: the same opportunity can arise with differential pressure meters. This has been known for many years. In 1986 Martin [1] showed that the use of an additional upstream pressure measurement would give the possibility of correcting the measured flowrate to account for the effect of different upstream installations. He measured the ratio of the pressure rise into the upstream corner of an orifice plate to the differential pressure: a change in this pressure rise ratio is proportional to the change in discharge coefficient due to certain upstream flow conditions. In more recent years Steven [2] and Skelton et al [3] have shown the benefits of using an additional pressure tapping around 6*D* downstream of an orifice plate so that the permanent pressure loss can be combined with the differential pressure to give information on the acceptability of the measurement. Departures from the anticipated pressure loss ratio can be attributed to different meter fault conditions or potential errors in measurement. This principle can be extended to other differential pressure devices such as Venturi meters and cone meters. This patented finding has been developed into a commercial software monitoring tool called ‘Prognosis’, which can be used to monitor the different measurement values, compare them with predicted or baseline measurements and then indicate departures from the norm as a diagnostic tool.

2 OBJECTIVES AND APPROACH

The main objective of this project for National Grid was to investigate the use of an additional pressure loss measurement in an orifice plate installation to generate diagnostic information. The usual differential pressure is measured from the flange tappings. An additional differential pressure is measured from the upstream (and the downstream) tapping to an additional tapping located some diameters downstream: a distance of six pipe diameters (6*D*) from the orifice plate is used as it is around the first location at which the pressure has recovered. A particular question to be addressed was whether a change in the discharge coefficient can be related to a change in the measured ratio of pressure loss to differential pressure.

A paper on the theory [4] written as a result of this project covers Computational Fluid Dynamics (CFD) simulations and other calculation methods to determine the ratio between the pressure loss and the standard differential pressure and to see how the ratio is correlated with change in discharge coefficient. The flow simulations covered the effects of axisymmetric profiles (both flatter and more peaked than that in a long straight pipe), an asymmetric profile and a swirling profile. They also covered the effect of a deposit on the upstream surface of an orifice plate, a fault condition which is a different type of poor installation and may occur during service. A common fault of having an orifice plate installed incorrectly by reversing the plate was also examined. This latter fault condition gives rise to large measurement errors which are undetectable through the normal measurement process.

This paper describes the experiments that have been carried out to measure the effect of a series of fault conditions described in detail in Section 3.2.

The experiments were carried out using the NEL water flow test facility. The data were collected from the NEL data acquisition system. This recorded the average of the differential pressures, six in all, the flowrate and the water temperature taken across defined test periods with a reference flowmeter measuring the continuous flowrate. A network diagram of the flow loop is shown as Figure 1 and a photograph of the orifice meter as Figure 2.

The six differential pressures were transmitted in real time to the commercial 'Prognosis' software where they were recorded and analysed against pre-set fault limits.

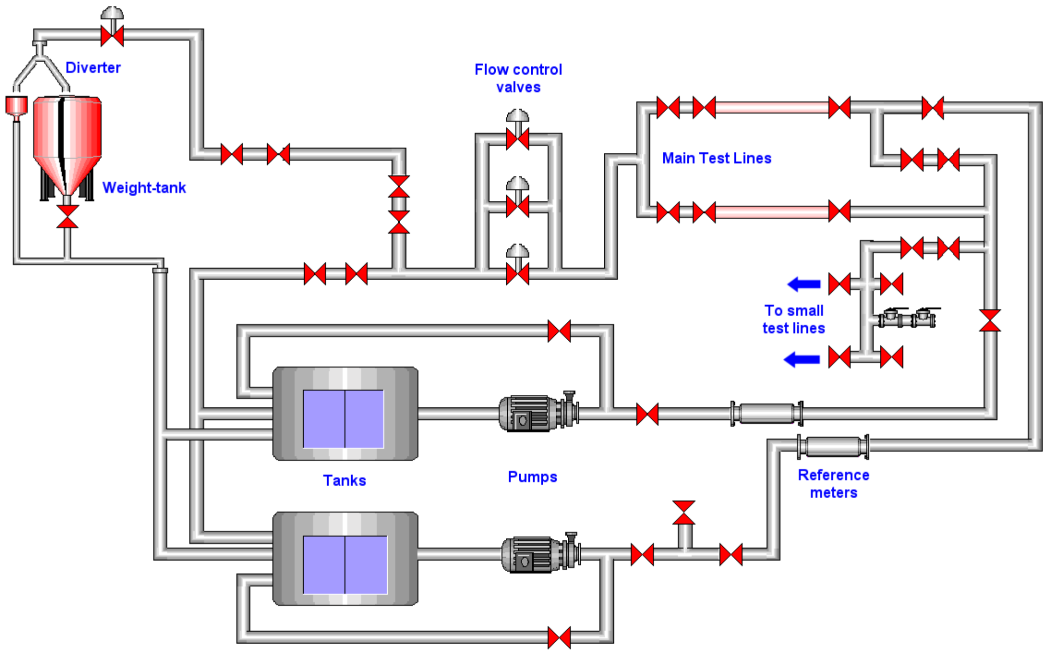

Figure 1 Diagram of the flow loop: the orifice meter was installed in the main test lines; reference meters were used

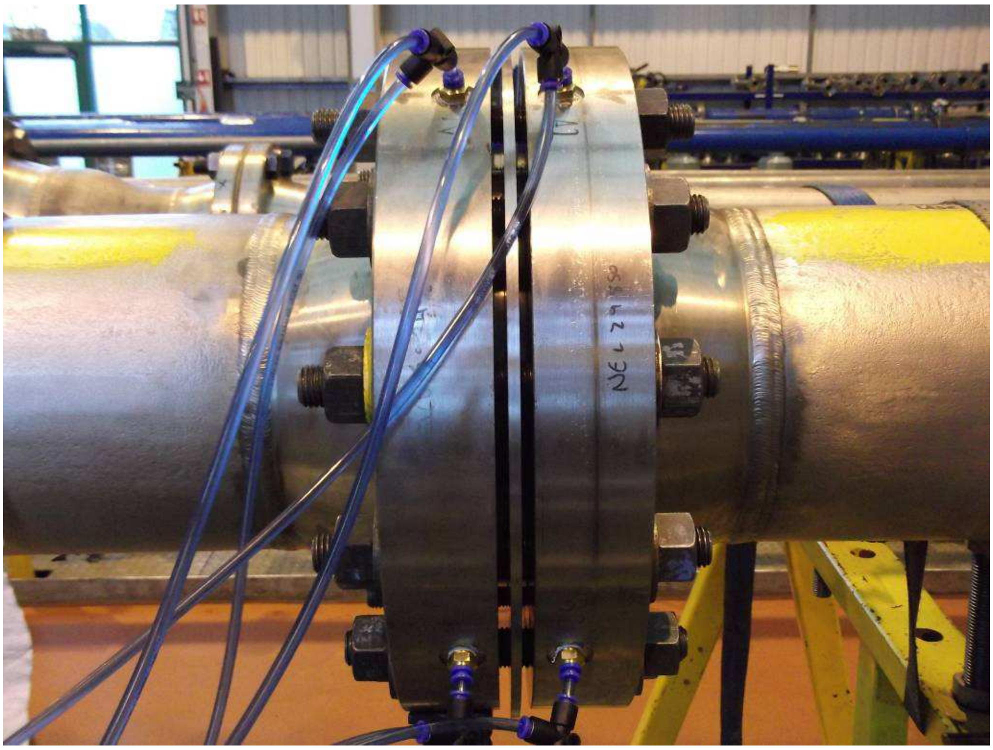

Figure 2 The orifice meter

3 EXPERIMENTAL WORK

3.1 General

Existing 8" (200 mm) diameter pipes manufactured as an orifice plate metering assembly with flange tappings were used: the internal diameter *D* was 202.56 mm. Upstream of the orifice plate there was 70*D* of straight pipe to a perforated plate flow conditioner and then 10*D* to a bend. The last 9*D* of the upstream pipe before the orifice plate was machined internally. Downstream of the orifice plate there was a 4*D* machined length and then a further length of matching machined pipe, 6*D* in length for the initial tests (see also 5.2). The assembly had pressure tappings available in two planes 90° apart.

To the additional pipe, bosses were added 6*D* downstream of the orifice plate so that the pressure loss could be measured. Data were collected in two planes perpendicular to each other (referred to as horizontal and vertical, although they were 30° below horizontal and 30° from vertical up; the dowel pins were located top and bottom). Seven orifice plates were manufactured (β = 0.2, 0.4, 0.6 (4 off) and 0.75) by a specialist fabricator. Care was taken to adhere strictly to the requirements of ISO 5167 and the orifice bores were spark eroded to ensure sharp edges. Multiple plates were required because some were to be damaged in order to produce fault conditions and could not be used subsequently.

Three differential pressures were measured:

1. the differential pressure: from the upstream flange to the downstream flange, ΔP
2. the measured pressure loss: from the upstream flange to 6*D* downstream of the orifice plate (not the actual pressure loss), PL

3. the measured pressure recovery from the downstream flange to 6*D* downstream of the orifice plate, PR

These measured differential pressures were taken as shown in Figure 3.

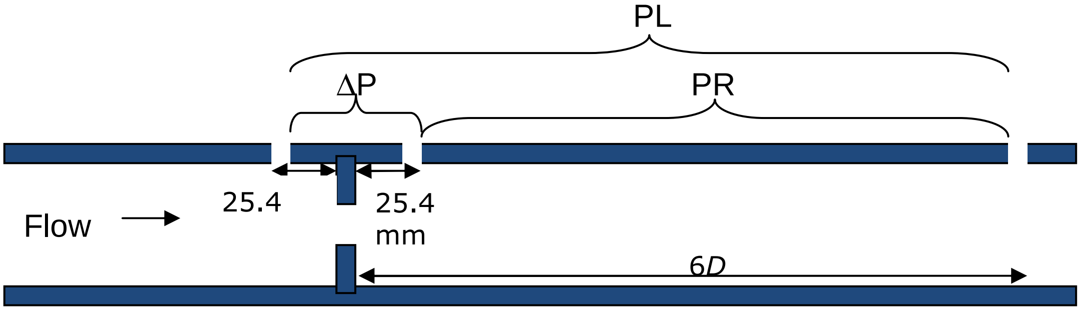

Figure 3 Measured differential pressures

From these measurements three diagnostic ratios are computed.

Pressure Loss Ratio (PLR) = Ratio of PL to ΔP
Pressure Recovery Ratio (PRR) = Ratio of PR to ΔP
Pressure Recovery to Pressure Loss (PRL) = Ratio of PR to PL

Throughout the project the difference between the differential pressure across the orifice plate and the sum of the measured pressure loss and the measured pressure recovery was calculated. The value of this sum relative to the measured differential pressure provides a strong diagnostic test. During testing 95% of the good points were within about 0.05%. This ratio was used to indicate the presence of air in the impulse lines. Because of the good agreement between the three differential pressures in this project there is very little need to consider pressure recovery data separately from pressure loss data except in two situations: for β = 0.2 where the pressure recovery is about 5% of the pressure loss (see 4.1) and where there was a deliberately introduced error in differential pressure.

3.2 Tests Undertaken

The actual tests undertaken were as follows:

1) Error in orifice plate diameter (entered value 1% higher than the true value)

2) Error in pipe diameter (entered value 2% higher than the true value)

3) Drift in differential pressure transmitter (measured value 2% higher than the true value)

NOTE 2% of value could, for example, be 0.2% of span when the transmitter is operated at 10% of span.

4) Incorrectly positioned orifice plate (offset by 6.3 mm (an eccentricity of 3.1% of *D*) towards the horizontal tappings) – see Figure 4 (there was no leak around the outside of the orifice plate).

NOTE If this offset was due to the orifice plate not being fully seated at the bottom of the meter tube then the 'vertical' tappings would be on the side of the orifice meter and the 'horizontal' tappings would be on the top.

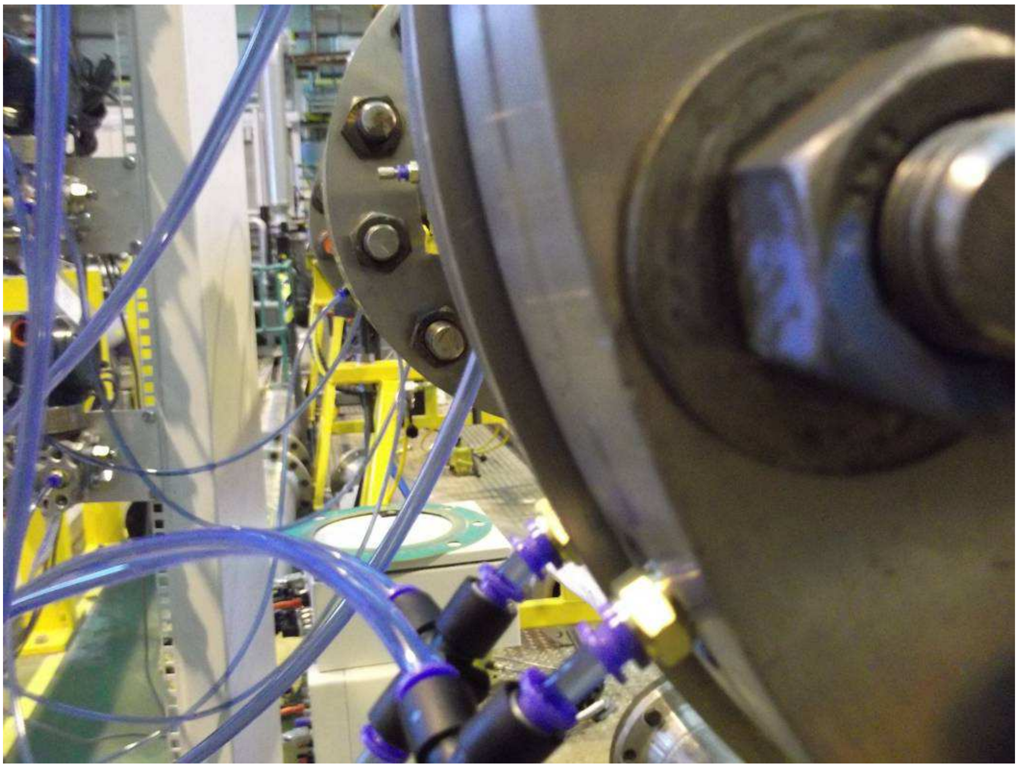

Figure 4 Orifice plate offset towards the 'horizontal' tappings

5) Rounded orifice edge (edge radius = 0.23 mm, i.e. r/d = 0.0019)

6) Rounded orifice edge (edge radius = 0.42 mm, i.e. r/d = 0.0035) – see Figure 5

Figure 5 Rounded edge of orifice plate

7) Unexpected drain hole (drain hole of radius = 0.1d not included in calculation) – see Figure 6

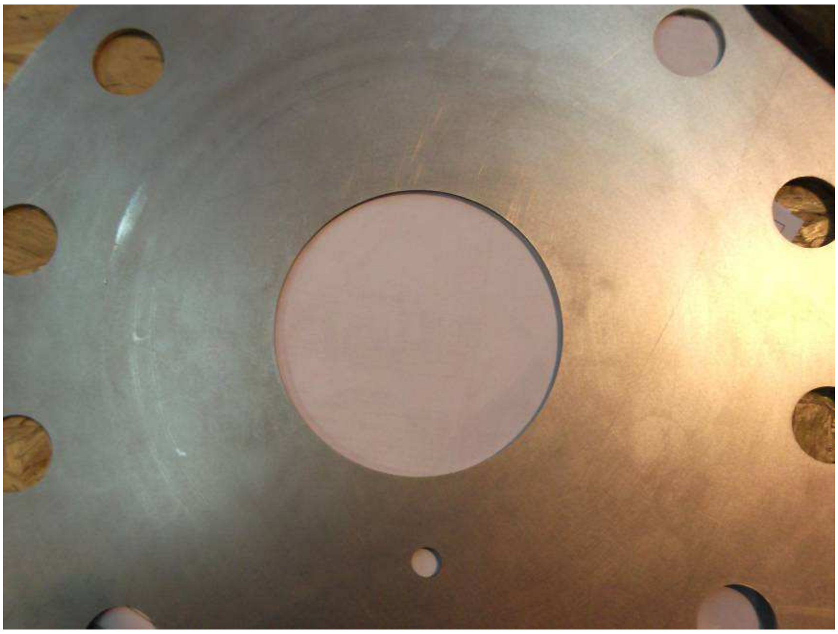

Figure 6 Orifice plate (β = 0.6) with drain hole

8) Deposit on the face of the orifice plate, simulating face contamination (a gasket of thickness 1.5 mm covering most of the upstream face leaving a clear zone of width 7 mm) – see Figure 7

9) Deposit on the face of the orifice plate, simulating face contamination (a gasket of thickness 1.5 mm covering most of the upstream face leaving a clear zone of width 5.25 mm)

10) Deposit on the face of the orifice plate, simulating face contamination (a gasket of thickness 1.5 mm covering most of the upstream face leaving a clear zone of width 4.8 mm)

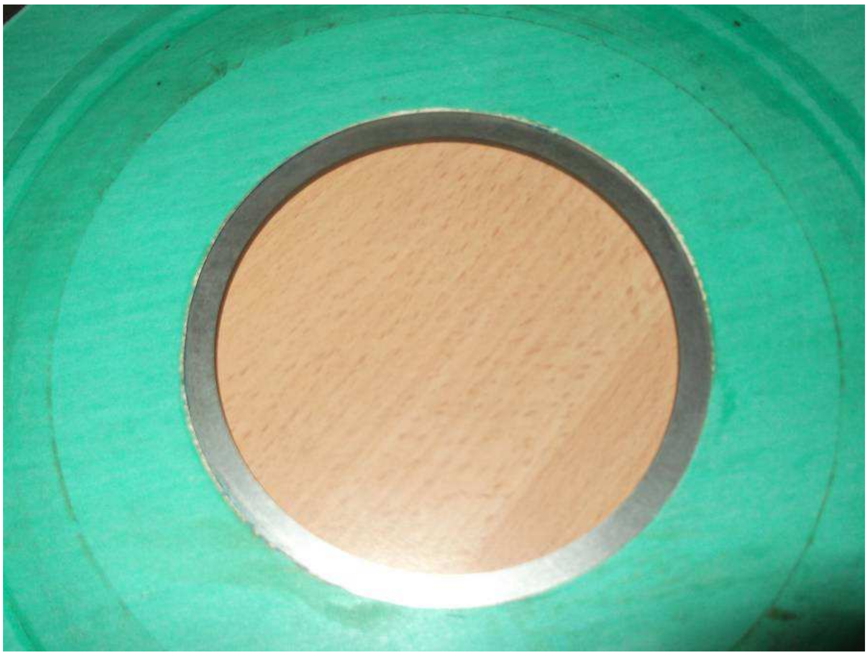

Figure 7 Orifice plate with gasket simulating face contamination

11) Two phase flow (adding bubbles to the water)

12) Plate installed backwards

13) Simulation of a partially blocked flow conditioner (using a gate valve 1/3rd closed, downstream end 7*D* from orifice plate) – see Figure 8

14) Simulation of a partially blocked flow conditioner (using a gate valve 2/3rds closed, downstream end 7*D* from orifice plate)

Figure 8 Simulation of a partially blocked flow conditioner (using a partly closed gate valve)

15) Bent plate (deviation from flat approximately linear with distance from pipe wall, maximum deviation from flat about 5 mm) – see Figure 9

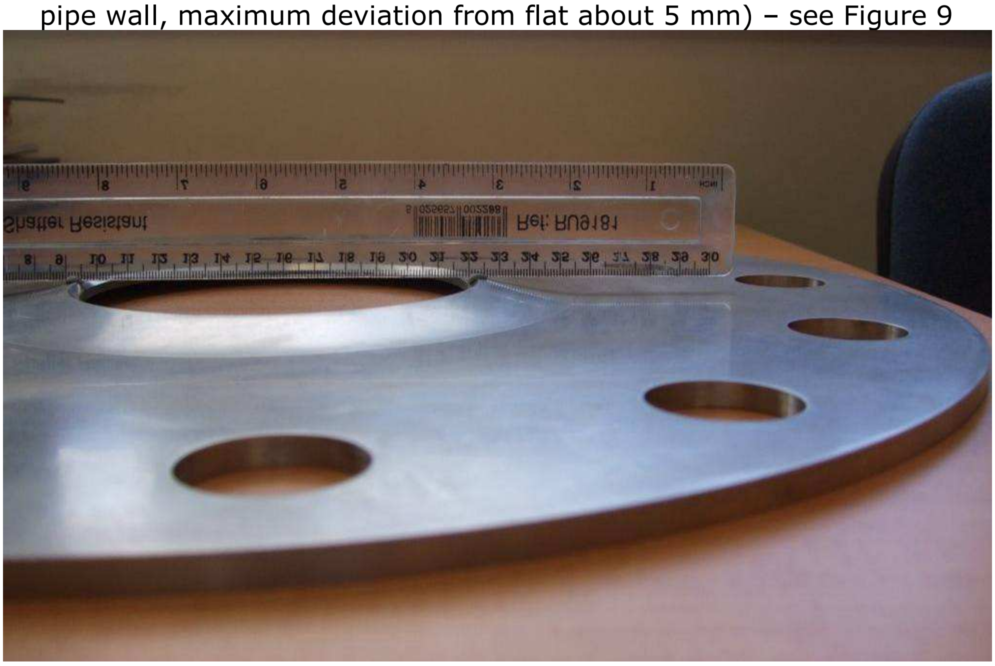

Figure 9 Bent orifice plate

All these tests were carried out using a β = 0.6 orifice plate except tests 4), 10) and 13), which were only done with β = 0.75. β = 0.75 was used instead of β = 0.6 for tests 4) and 13) to give a larger shift in discharge coefficient.

Test 7) was carried out with β = 0.2, 0.6 and 0.75.

Test 12) was carried out with β = 0.2 and 0.6.

Test 14) was carried out with β = 0.6 and 0.75.

To present the data, a baseline test was provided without any fault condition. In each case the baseline data were fitted as a function of $(10^6/Re_D)^{0.5}$ and the mean deviation from the fitted line calculated for inclusion in subsequent work. An example from the orifice plate deposit tests is shown in Figures 10 and 11. This shows both the baseline calibrations and the results when the fault is introduced. Figure 10 shows the change in discharge coefficient whereas Figure 11 shows the change in measured pressure loss.

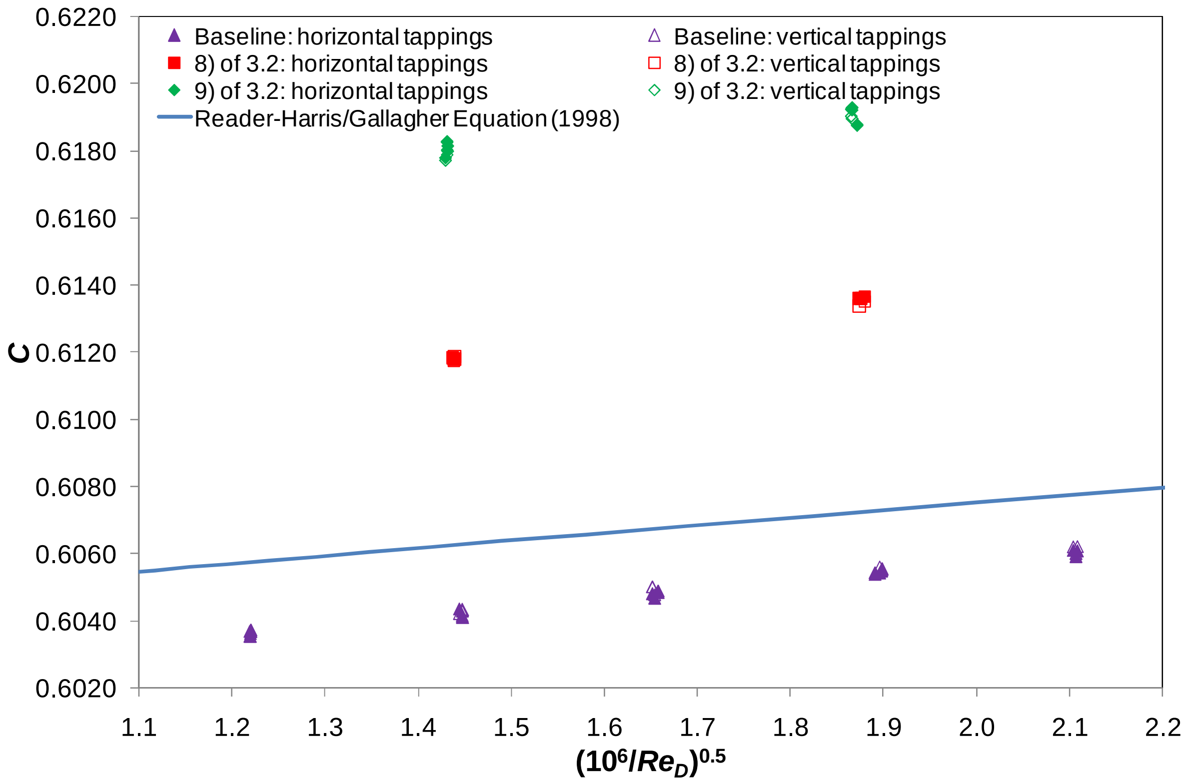

Figure 10 Effect of the deposit on the orifice plate on the discharge coefficient: β = 0.6

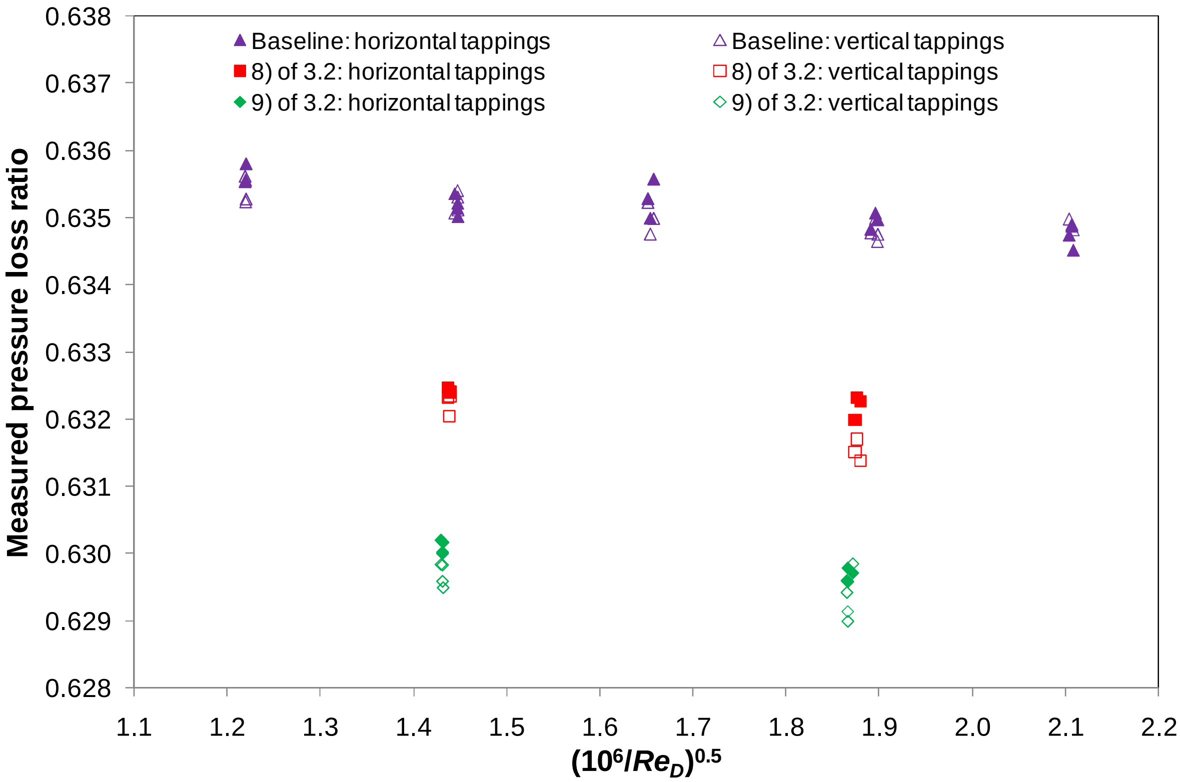

Figure 11 Effect of the deposit on the orifice plate on the measured pressure loss ratio: β = 0.6 (data corrected)

From these measured data, the relative changes in discharge coefficient and pressure loss were derived and presented as the result of the experiment.

Correction to the data has been carried out: the correction is related to the manufacture of the downstream pressure tapping and is fully explained in section 5.2. For analyses against an established base line the correction makes very little difference.

4 WITH AN INITIAL BASELINE

4.1 General

Where an orifice plate is installed and records of the pressure ratios are taken across the flow range, a baseline can be established. Departures during service from these baseline values can then be attributed to a fault developed on the system, i.e. the PLR trends can be monitored in service to identify developing faults. Potential faults have been simulated in the testing programme in order to determine the difference from the baseline.

4.2 With an Initial Baseline: Single-Phase Flow β = 0.2 Orifice Plate

The β =0.2 plate was tested during test 7) – unexpected drain hole - and test 12) - reversed plate. These results are shown in Figure 12. An unexpected drain hole fault will be caused by installing a plate with a drain hole, but not including the hole in the calculation software. A similar fault condition (but causing an error of opposite sign) is a drain hole becoming blocked in service.

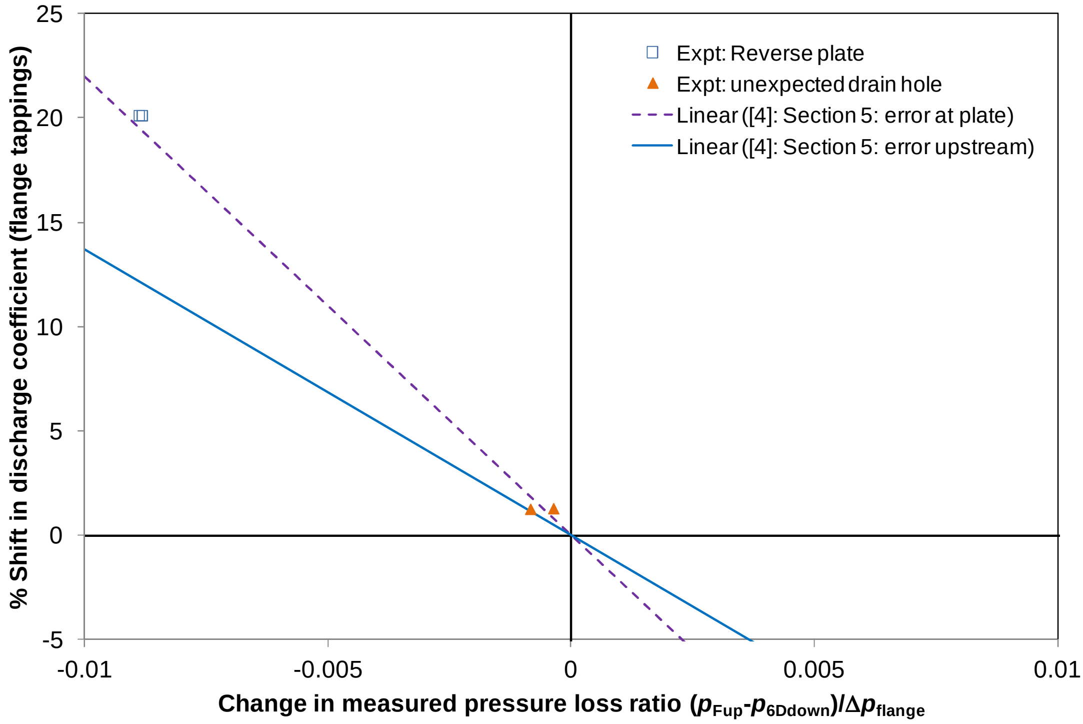

Figure 12 Shift in discharge coefficient from baseline vs Change in measured pressure loss ratio: β = 0.2 orifice plate

The two results for each condition are derived from the two sets of pressure tappings 90° apart.

For each plate the Computational Fluid Dynamics (CFD) results taken from a theoretical study previously reported [4] have been shown. These results have been included to demonstrate that the experimental and the CFD results are in good agreement with each other. The calculated values as derived in Section 5 of [4] are also included.

Installing an orifice plate in the reverse direction gives a change in discharge coefficient of about 20%. It is clearly shown by a change in pressure loss ratio of about -0.009. This can be measured.

The drain hole gives a change in discharge coefficient of about 1.3%. The pressure loss data are shown in Figure 13: it would be very difficult from the PLR data in the case of the unexpected drain hole for the β=0.2 orifice plate to be sure that there is a problem.

In this case because the pressure recovery is so much smaller than the pressure loss more discrimination can be obtained by considering the pressure recovery ratio (PRR). The pressure recovery data are shown in Figure 14: it might be possible from the PRR data in the case of the unexpected drain hole to be sure that there is a problem.

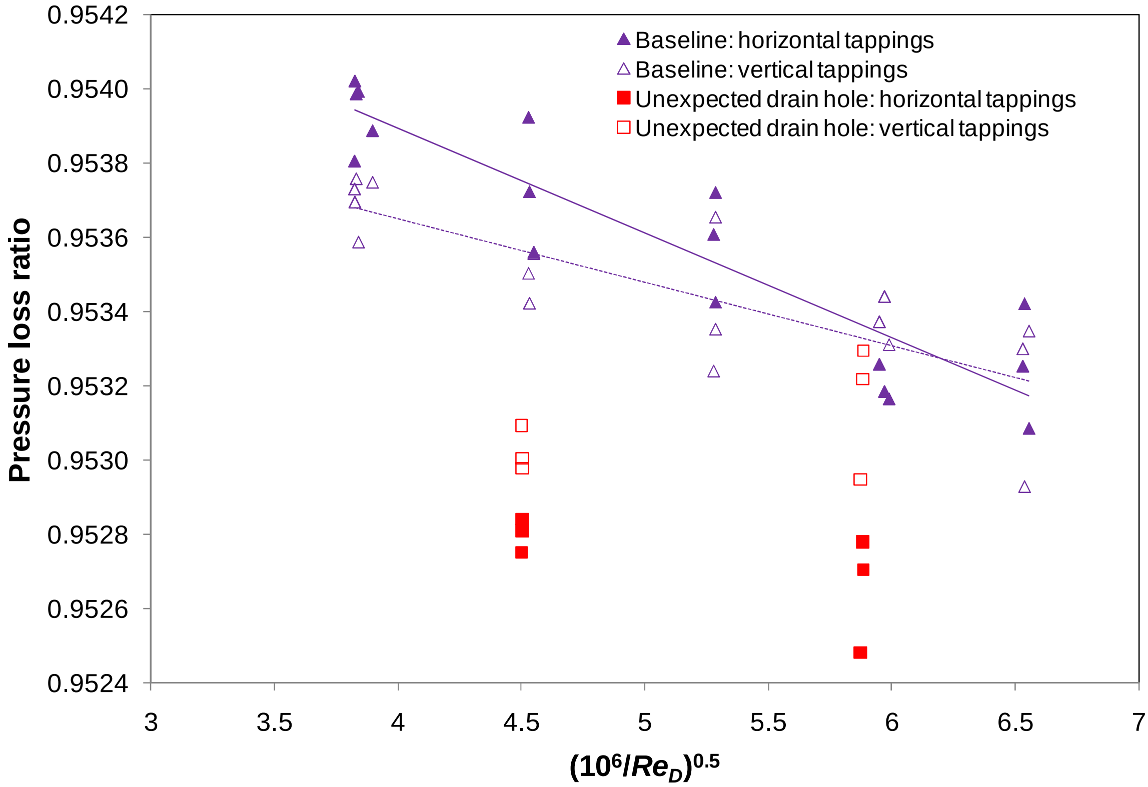

Figure 13 Effect of unexpected drain hole of diameter 0.1*d* on measured pressure loss ratio: β = 0.2 orifice plate

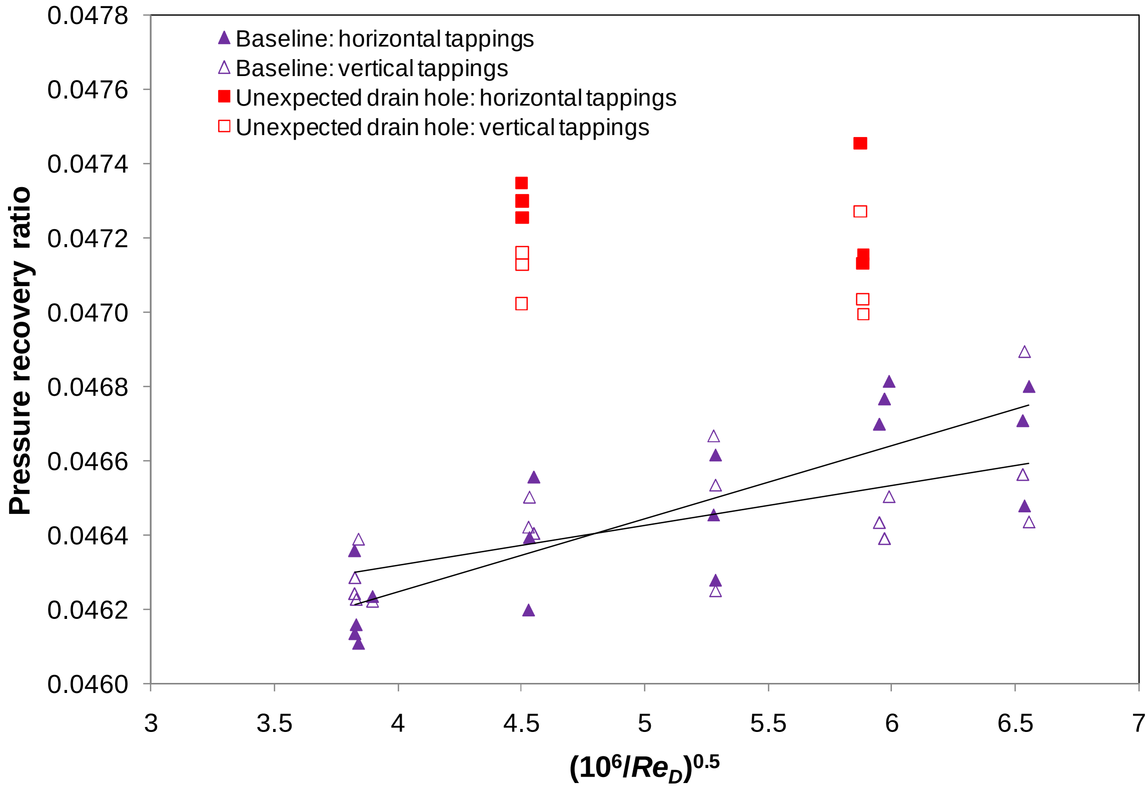

Figure 14 Effect of unexpected drain hole of diameter 0.1*d* on measured pressure recovery ratio: β = 0.2 orifice plate

4.3 With an Initial Baseline: Single-Phase Flow with β = 0.6 And β = 0.75 Orifice Plates

Again the initial baseline differential pressures were established prior to testing and changes from the baseline were determined for each orifice plate and fault condition.

The β =0.6 orifice plates were tested in single-phase flow during tests 1) to 3), 5) to 9), 12), 14) and 15). Tests 5) and 6) use the same symbol; similarly tests 8) and 9) use the same symbol. The results are shown in Figure 15a. To give additional clarity Figure 15b shows the same data except for those with a reversed plate. This allows the remaining results to be shown with higher resolution.

In practice the error in differential pressure ('dp error') led to a failure to achieve the balance PL + PR = ΔP (see the final paragraph of 3.1); so this point on Figures 15a and 15b is irrelevant.

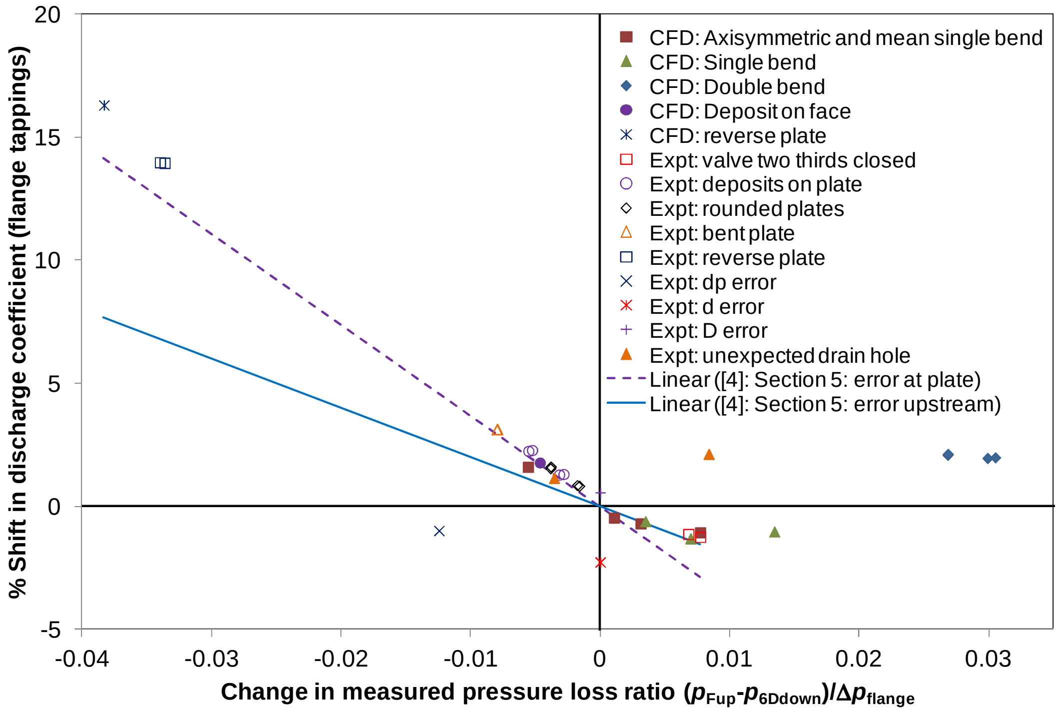

Figure 15a Shift in discharge coefficient from baseline vs Change in measured pressure loss ratio: β = 0.6 orifice plate

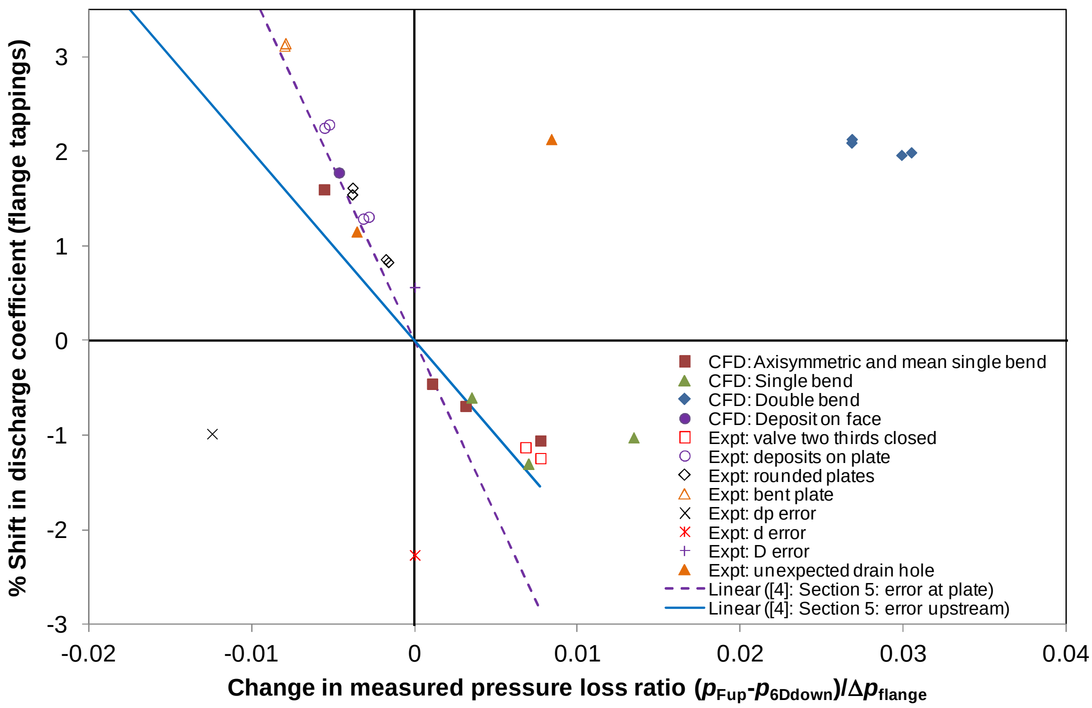

Figure 15b Shift in discharge coefficient from baseline vs Change in measured pressure loss ratio: β = 0.6 orifice plate (omitting reversed plate)

The Prognosis image for the bent plate is shown as Figure 16. The fact that the points lie outside the box show that Prognosis would find this problem. Further details about the interpretation of the Prognosis image can be found in [3]. The date in the Figure is that when the image was produced, not when the data were taken.

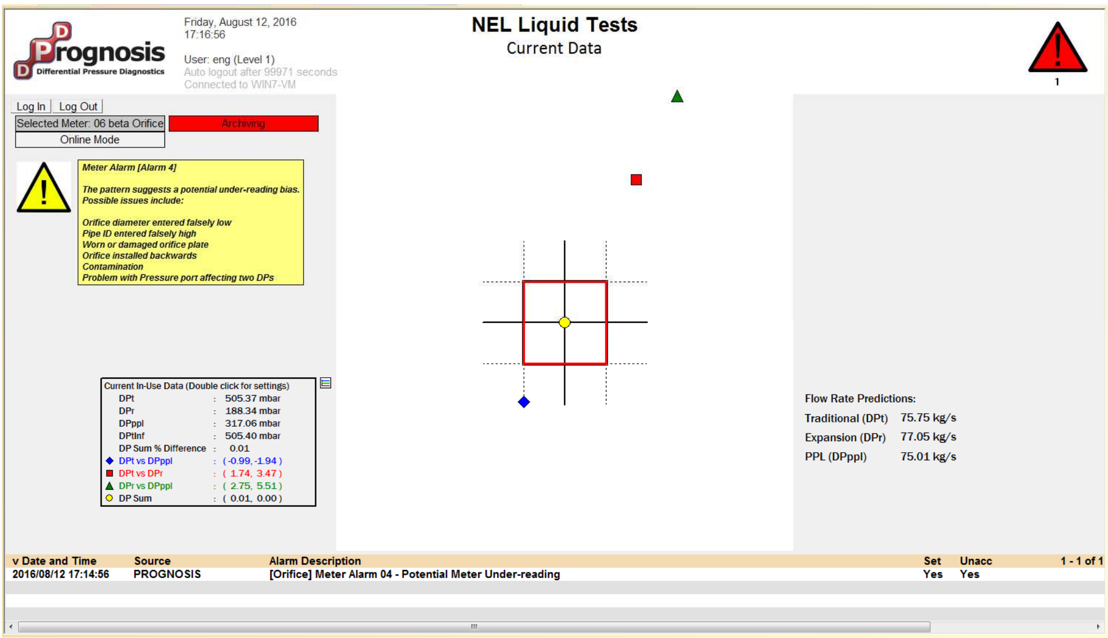

Figure 16 Prognosis image for flow downstream of a bent plate: β = 0.6 orifice plate

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The β =0.75 orifice plates were tested in single-phase flow during tests 4), 7), 10), 13), and 14). The results are shown in Figure 17.

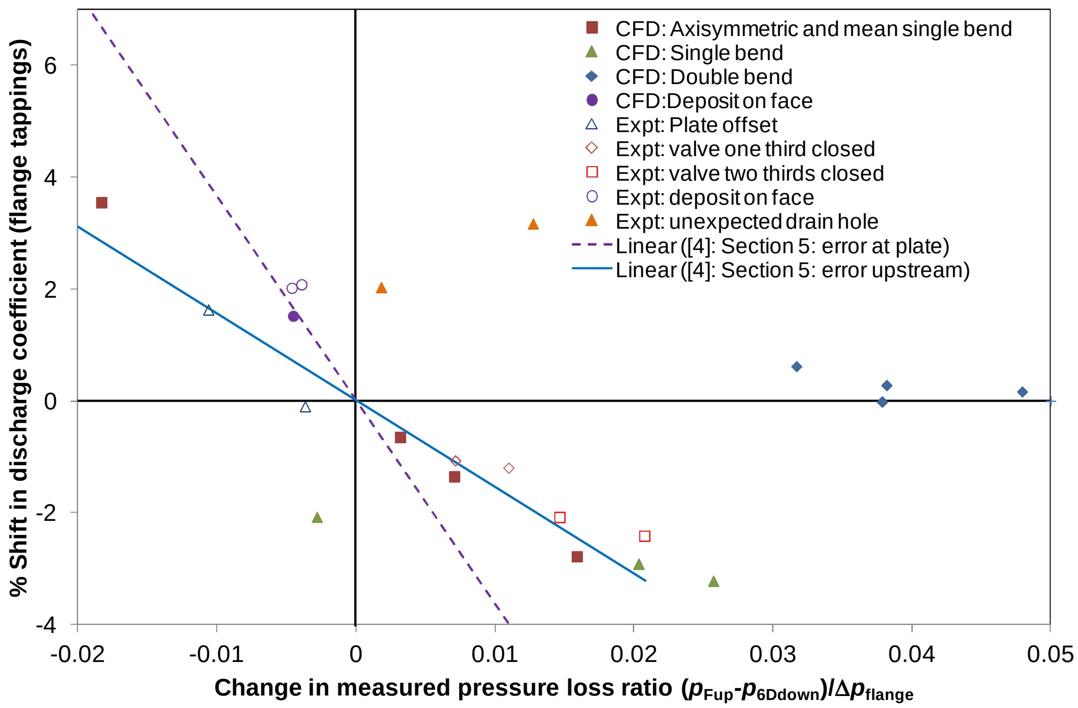

Figure 17 Shift in discharge coefficient from baseline vs Change in measured pressure loss ratio: β = 0.75 orifice plate

The Prognosis images for a valve one third closed and two thirds closed are shown as Figures 18a and 18b. The fact that the points lie outside the box show that Prognosis would find both these problems.

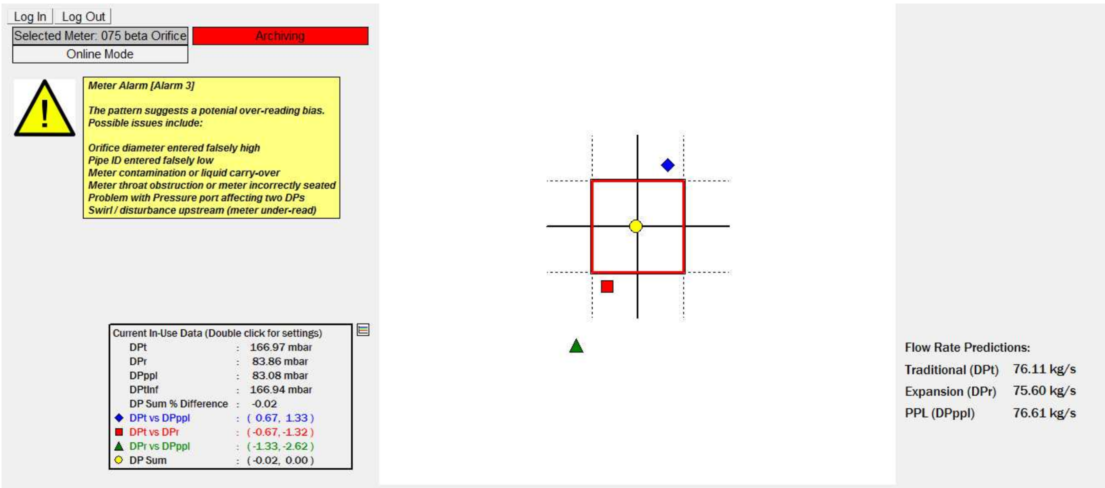

Figure 18a Prognosis image for flow downstream of a valve one third closed: β = 0.75 orifice plate

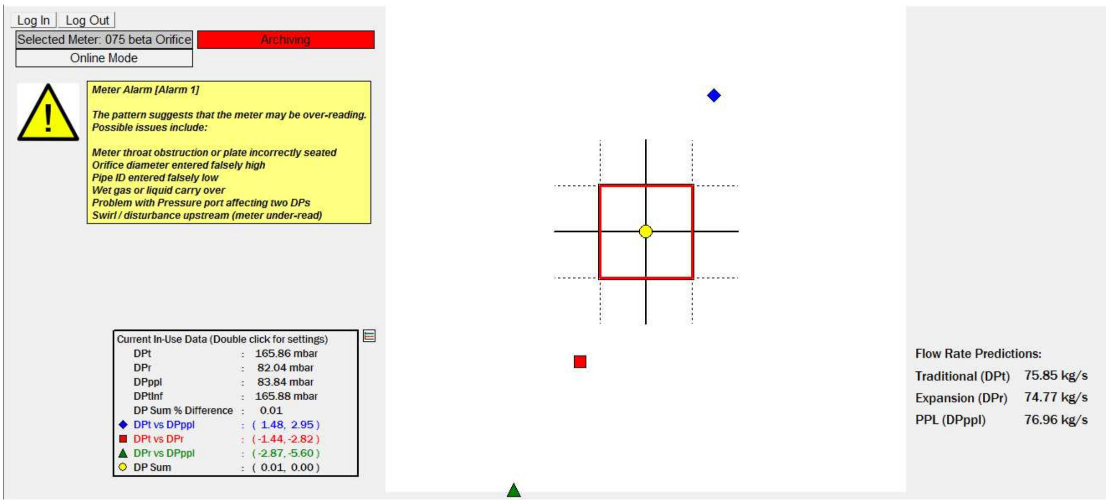

Figure 18b Prognosis image for flow downstream of a valve two thirds closed: β = 0.75 orifice plate

From Figures 15 and 17 it is clear that, for β = 0.6 and 0.75, if a change of less than 0.0025 in measured pressure loss ratio is measured, then provided that there is not a mistake (wrong entry of diameters, presence of unexpected drain hole) it is unlikely that there is a shift in discharge coefficient greater than 1% from the original condition.

As expected from the report on the theory [4] the effect of many types of installation is proportional to the difference in the pressure loss ratio; however, as expected, the constant of proportionality depends on whether the fault is at the orifice plate itself or in the upstream pipework.

So it is clear that a shift in discharge coefficient can be spotted by looking at the change in the pressure loss ratio. Moreover, if errors due to mistakes (wrong entry of diameters, presence of unexpected drain hole) are avoided and the orifice plate is known from inspection to be in good condition it may be possible to assume the error is upstream (e.g. a partially blocked conditioner or a roughened pipe) and to estimate the error.

The challenge in practice is to ensure that the sensitivity of the pressure measurements can resolve a change in PLR to within 0.0025. It is also important to recognise that this sensitivity is based on a comparison with measured and recorded baseline values of PLR rather than on comparison with a standard prediction of the PLR in good conditions.

PRR gives a little more discrimination than PLR, but the pattern is almost identical. PRL gives a further improvement in discrimination, but again with a very similar pattern.

4.4 With an Initial Baseline: with Added Gas Bubbles

For liquid flows it is possible that gas can be entrained in the flow. The presence of gas is known to give errors in the measurement. Gas volume fractions of up to approximately 1.5 % were produced by introducing air to the water flow. This produced errors in discharge coefficient of up to 2.5 % for pressure tappings near the top of the pipe.

The data with added gas bubbles cannot easily be shown on the same graph as the other data since the data were taken over a range of gas volume fractions. The data are shown in Table 1. It is clear that in general there is good agreement between the differential pressure and the sum of the measured pressure loss and the measured pressure recovery, but that as air accumulates in the pressure tapping near the top of the pipe the agreement becomes less good. This diagnostic measurement may indicate the presence of gas gathering at the top of the pipe when the tappings are also near the top of the pipe.

From Figure 19 for both pairs of tappings the PLR clearly indicates the presence of gas in the flow. It can be seen that using the pressure tappings just below the horizontal the relationship between the shift in *C* and the change in measured pressure loss ratio is similar to that in Figure 15 with the error upstream: the performance of the orifice plate with these pressure tappings is much better than its performance with pressure tappings near the top of the pipe because in the former case gas does not accumulate in the impulse lines (impulse lines for liquid metering should always slope downwards lest gas accumulate within the pressure tappings and cause errors, as found, for example, in Table 1 with vertical tappings). The relationship between shift in discharge coefficient and PLR for the vertical tappings probably reflects more the amount of air held within the tapping and impulse line than the gas volume fraction.

Table 1 Data collected with added gas bubbles

Water Re_D	% Gas Volume Fraction	% difference in sum of pressure loss and pressure recovery from differential pressure		% shift in *C* from baseline		Change in measured pressure loss ratio from baseline	
		Horizontal tappings	Vertical tappings	Horizontal tappings	Vertical tappings	Horizontal tappings	Vertical tappings
471594	No gas injection	0.02	-0.01	0.03	0.04	0.0004	0.0000
471256	0.04	0.02	-0.01	0.00	-0.01	0.0003	-0.0017
470357	0.11	0.03	-0.01	-0.02	0.00	0.0003	-0.0012
470284	0.14	0.02	-0.01	-0.06	-0.07	0.0007	-0.0016
351946	No gas injection	0.01	-0.03	-0.03	-0.02	0.0001	-0.0037
347068	0.41	0.01	-0.03	-0.21	-0.24	0.0014	-0.0087
340432	1.16	0.00	-0.03	-0.53	-0.23	0.0016	-0.0062
275989	No gas injection	0.01	-0.04	-0.02	0.85	0.0006	-0.0035
265898	1.57	0.00	-0.06	-0.57	2.13	0.0032	0.0088
269013	1.11	0.01	-0.05	-0.23	2.43	0.0014	0.0092

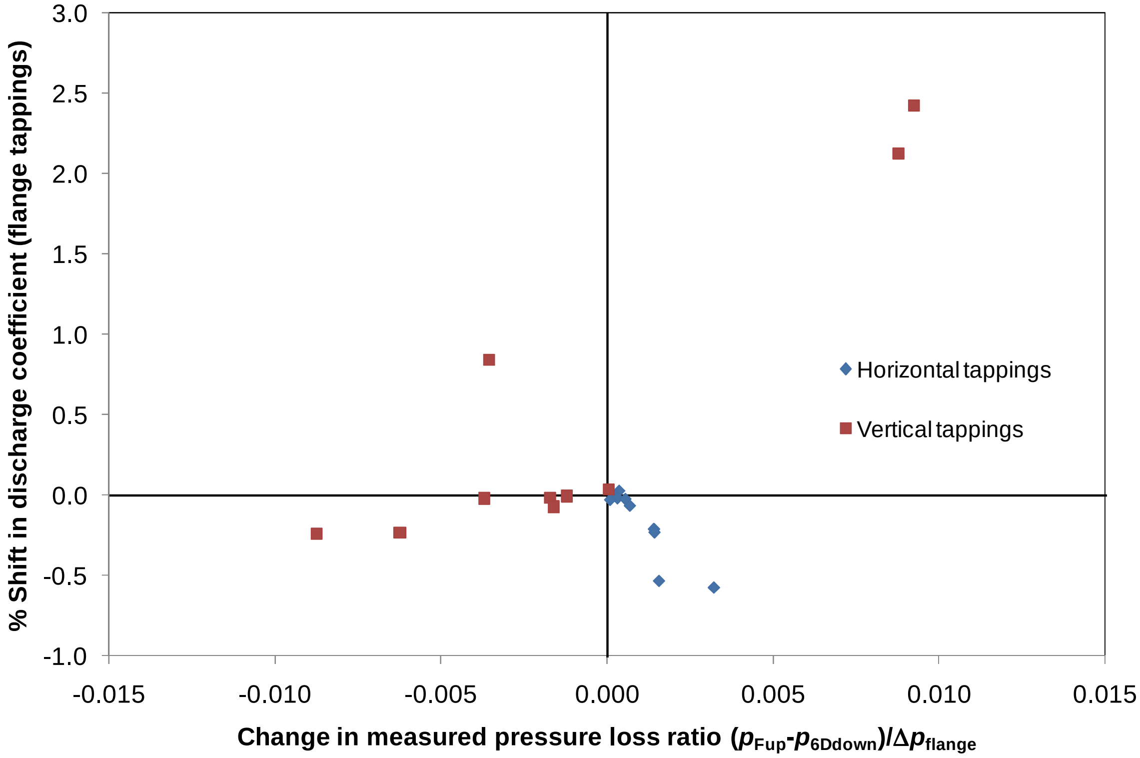

Figure 19 Shift in discharge coefficient from baseline vs Change in measured pressure loss ratio for tests with added gas bubbles: β = 0.6 orifice plate

5 WITHOUT AN INITIAL BASELINE

5.1 General

It is more difficult to know whether an orifice metering system is functioning correctly when there is no preliminary measurement of pressure ratios when the installation is first installed and put into service with, presumably, correctly designed pipe, plate and associated instrumentation.

To carry out diagnostic tests with no baseline, the various pressure ratios are tested against those predicted for the installation. This in effect creates a (theoretical) baseline. Comparing against a theoretical baseline will, however, potentially lose significant sensitivity in comparison with establishing and using a measured baseline.

5.2 Effect of Pipework

An important finding in relation to the installation of the additional 6*D* pressure tapping was made during the testing and shows how important the condition of the downstream pipe is if diagnostics without a measured baseline are not to be misleading.

The orifice meter used in this project was very well made; the downstream pipe with the additional tappings was made by taking an existing high-quality length of machined pipe and welding additional tappings to it: a reputable pipework contractor spark-eroded the 6*D* tappings to ensure the tapping ports and locations were of the highest quality.

On inspection it was noticed, only by very careful examination of the clean pipe, that the heat from welding had locally distorted the pipe creating an inward bulge at the tapping. The distortion was discernible to the eye and by a finger, but was measured as only about a 0.8 mm inward bulge. An attempt was made to heat the pipe and reduce the distortion. This reduced the distortion to about 0.6 mm. Once this fault in the pipe had been observed, a fault which could easily occur when a tapping is added to a pipe and the pipe is not subsequently machined, the effect on the diagnostic information was investigated. The exact size of the bulges is difficult to determine because the heat has made the pipe slightly oval.

Firstly CFD was carried out to check the effect. This suggested that with a hump or bulge of 0.65 mm with the tapping centrally located on the bulge the difference in measured pressure loss from that measured with a tapping on a pipe without a bulge would be unacceptably large.

While this work was being carried out, experimental testing continued with the pipe with the bulge. The diagnostics showed almost all the pressure loss ratio baselines as unacceptable. To investigate further and to provide correct results a new pipe with no distortion (that is with the tappings welded on and then the pipe machined and then the tappings spark eroded) was manufactured. The new pipe was of length 4*D*.

Most of the data were taken with the original downstream pipe, but some were collected with the new pipe; so it was necessary to correct all the results to what they would have been using the new pipe.

Accordingly baselines were taken for β = 0.75, 0.6 and 0.4 orifice plates with both downstream pipes in turn so that it was possible to calculate the correction required: see Figure 20. Then all the results presented in this report were corrected to the values that would have been obtained with the new pipe. Corrections to the measured pressure loss ratio were around -0.014 and -0.021 for β = 0.75 with the horizontal and vertical tappings respectively, and -0.0043 and -0.0062 for β = 0.6 with the horizontal and vertical tappings respectively. No measured corrections for β = 0.4 have been included in Figure 20 as their uncertainty is too high (although corrections based on extrapolation from Figure 20 corrected the baseline for the pipe with the bulge to within around 0.0003 of the baseline with the new pipe). The correction for β = 0.2 is negligible.

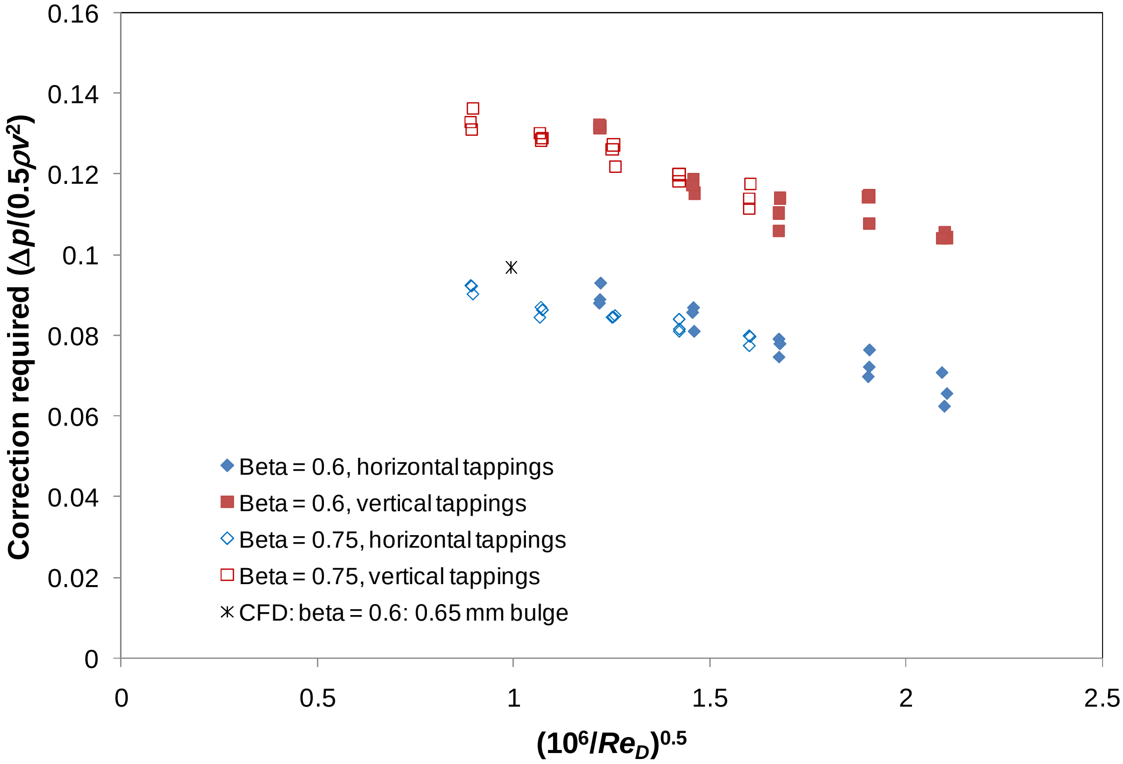

Figure 20 Correction required to the measured pressure loss (*v* is the mean velocity in the pipe)

5.3 Pressure Measurement Locations

Calculation of the discharge coefficient and hence the flowrate in an industry installation is done using the appropriate prediction from a standard – normally the Reader-Harris/Gallagher (1998) Equation as in ISO 5167-2:2003 [5]. A prediction of the pressure loss is also given in ISO 5167-2:2003, in particular the equation given in section 5.4.1 as:

$$\frac{\Delta\varpi}{\Delta p}=\frac{\sqrt{1-\beta^4(1-C^2)}-C\beta^2}{\sqrt{1-\beta^4(1-C^2)}+C\beta^2} \qquad (1)$$

This applies for a pressure loss measured using tappings approximately D upstream of the orifice plate and 6D downstream of the orifice plate. It is not specified what tappings should be used when determining C. This prediction is provided to allow the determination of total pressure loss for piping design purposes and is not provided for diagnostic purposes. It is entirely adequate for determining the pressure loss required to determine the temperature change from the downstream temperature measurement location to upstream of the plate (regardless of the choice of tappings for the determination of C in Equation (1)). It has an as yet unquantified uncertainty. Since this pressure loss prediction is based on the loss from approximately 1D upstream of the orifice plate to approximately 6D downstream of the plate, in practice this means that the measured upstream pressure if used for diagnostics will not match that required by the prediction if flange (or corner) tappings are used.

The deviation in measured PLR was evaluated from the NEL test work using the theoretical baseline derived in Equation (1) with *C* taken as the discharge coefficient using flange tappings as predicted by the Reader-Harris/Gallagher (1998) equation in ISO 5167-2: the results given in Figures 21 to 24 were obtained. As stated in 3.2 many more tests were carried out for β = 0.6 than for other values of β. Figures 21 and 22 show that this method works well for β = 0.2 and 0.4, but Figures 23 and 24 show that it works poorly for β = 0.6 and 0.75 since they imply that good flowrate measurements might be shown as errors and some poor flowrate measurements shown as acceptable. This is as expected from [4]. Error in mass flowrate has been shown in these figures rather than discharge coefficient since that relates better to the final use of the orifice measurement.

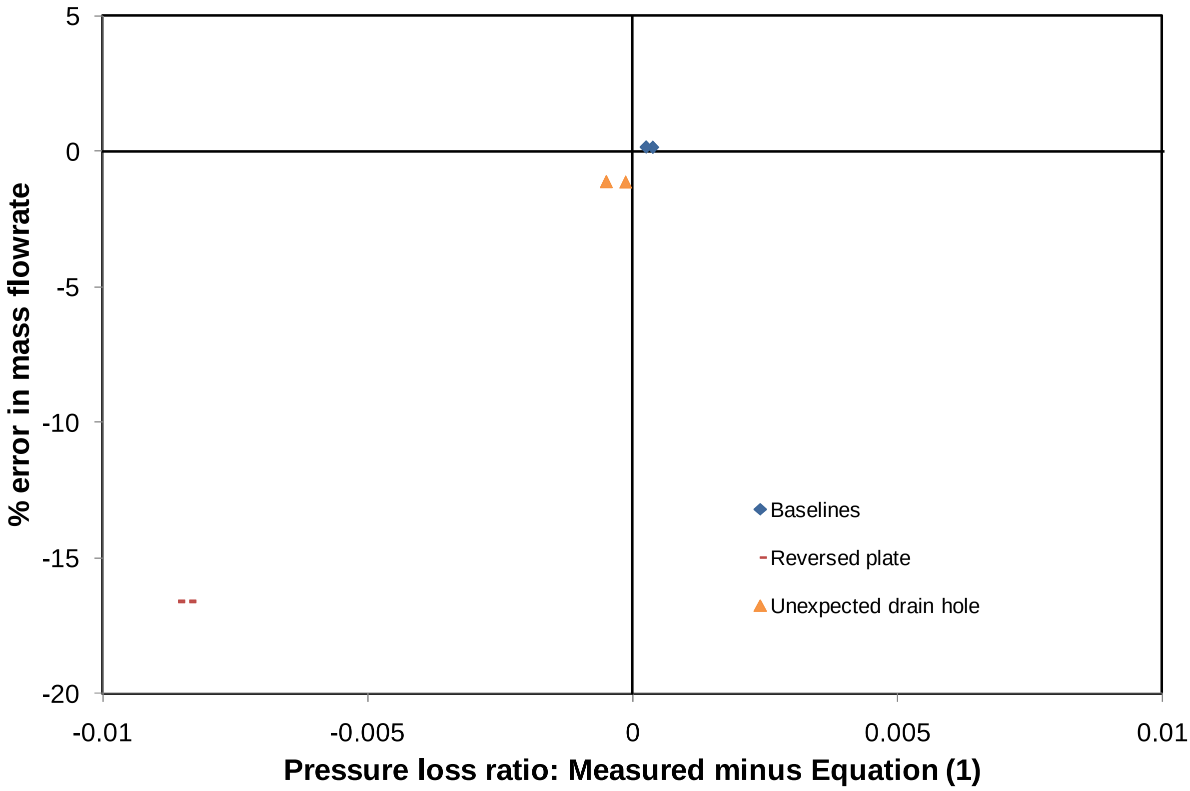

Figure 21 Error in mass flowrate using Reader-Harris/Gallagher (1998) Equation vs Deviation in measured pressure loss ratio from Equation (1): β = 0.2 orifice plate

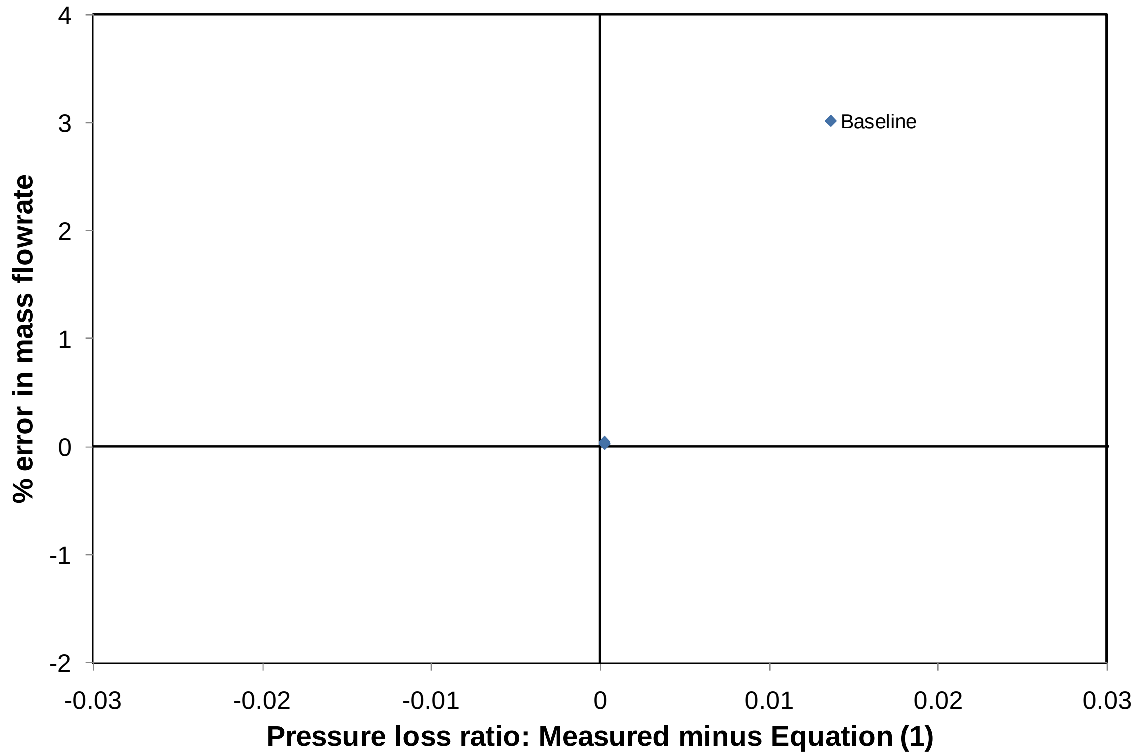

Figure 22 Error in mass flowrate using Reader-Harris/Gallagher (1998) Equation vs Deviation in measured pressure loss ratio from Equation (1): β = 0.4 orifice plate

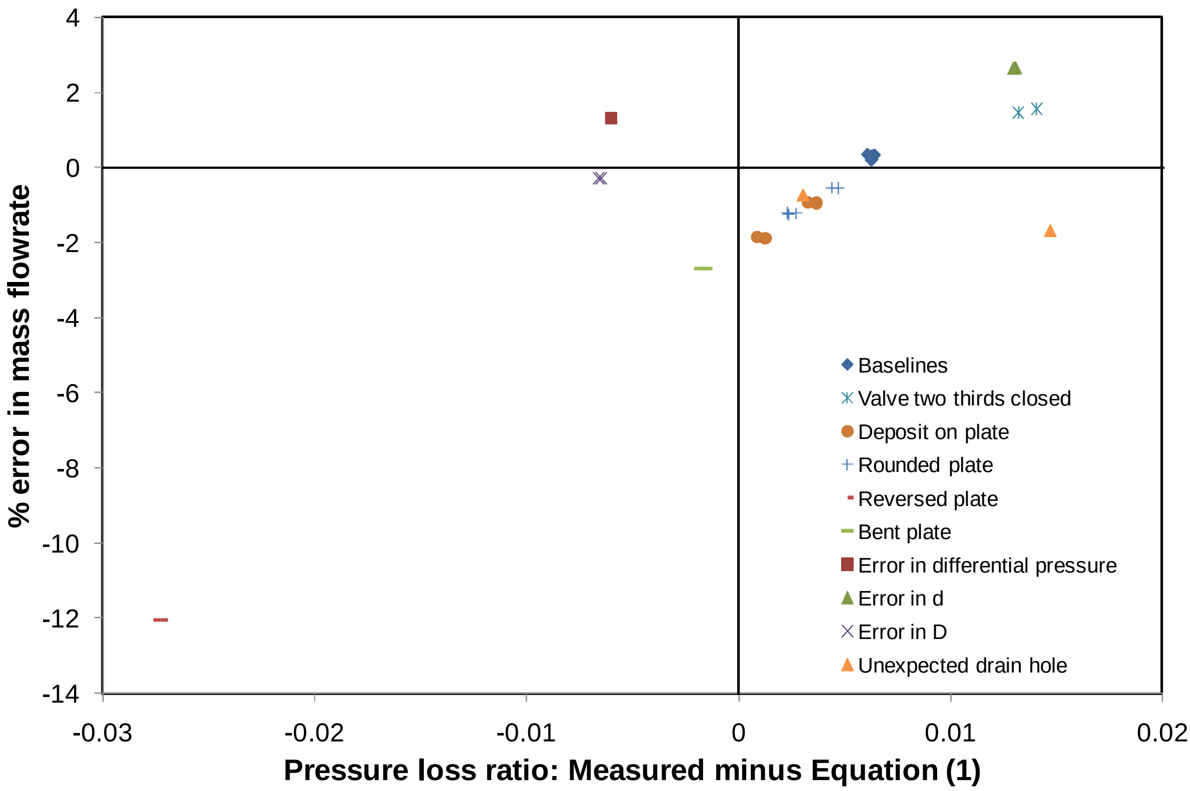

Figure 23 Error in mass flowrate using Reader-Harris/Gallagher (1998) Equation vs Deviation in measured pressure loss ratio from Equation (1): β = 0.6 orifice plate

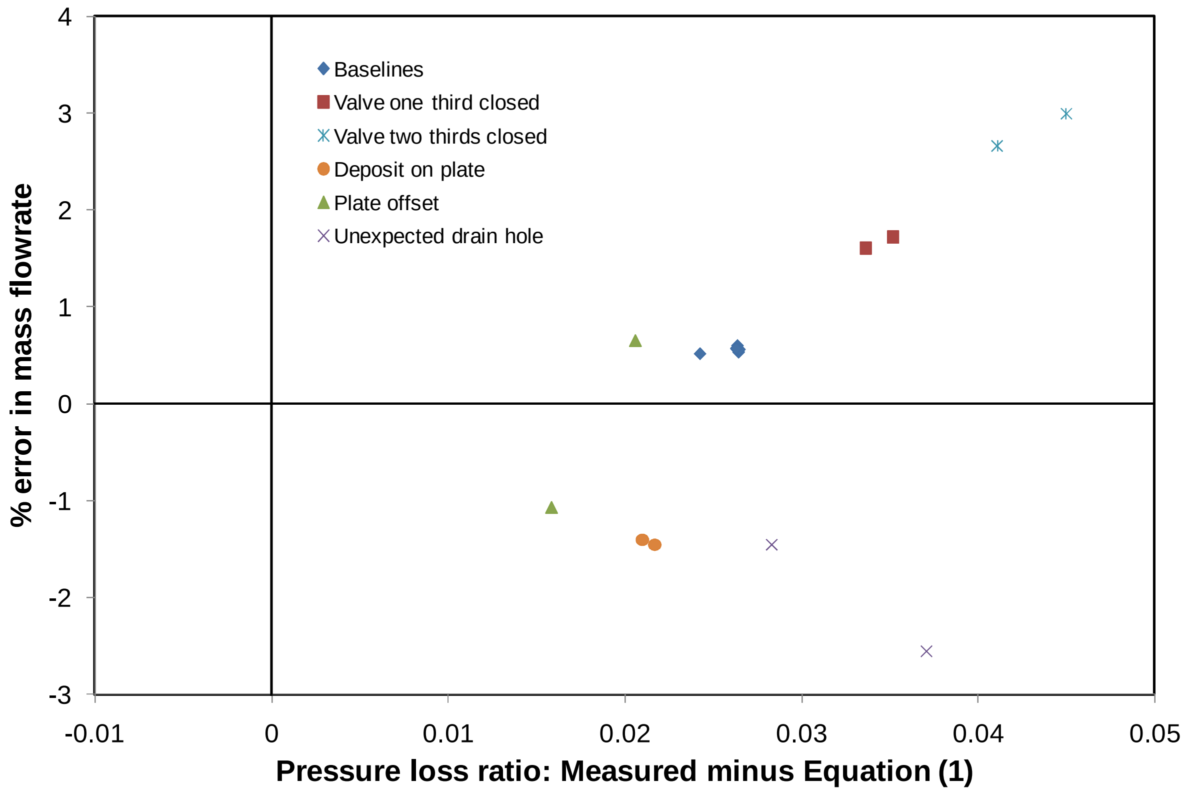

Figure 24 Error in mass flowrate using Reader-Harris/Gallagher (1998) Equation vs Deviation in measured pressure loss ratio from Equation (1): β = 0.75 orifice plate

A better option is to assume that the equation in 5.4.1 of ISO 5167-2:2003 (Equation (1) of this paper) is correct using tappings *D* upstream, at some point P downstream and around 6*D* downstream. Then

$$\Delta\varpi_{meas} = p_{rise} + \Delta\varpi$$

$$= p_{rise} + \frac{\sqrt{1-\beta^4(1-C_{DandP}{}^2)} - C_{DandP}\beta^2}{\sqrt{1-\beta^4(1-C_{DandP}{}^2)} + C_{DandP}\beta^2}\Delta p_{DandP} \quad (2a)$$

$$\Delta p_{flange} = \Delta p_{DandP} + p_{rise} - \Delta p_{fdowntoP} \quad (2b)$$

where $\Delta\varpi_{meas}$ is the pressure loss from the upstream flange tapping to 6*D* downstream, p_{rise} is the pressure rise from *D* upstream to the upstream flange tapping, Δp_{flange} is the differential pressure using flange tappings, Δp_{DandP} is the differential pressure using tappings *D* upstream and at P downstream, C_{DandP} is the discharge coefficient with tappings in those locations, and $\Delta p_{fdowntoP}$ is the pressure drop from the downstream flange tapping to the point P.

Then

$$\frac{\Delta\varpi_{meas}}{\Delta p_{flange}} = \frac{\dfrac{p_{rise}}{\Delta p_{DandP}} + \dfrac{\sqrt{1-\beta^4(1-C_{DandP}{}^2)} - C_{DandP}\beta^2}{\sqrt{1-\beta^4(1-C_{DandP}{}^2)} + C_{DandP}\beta^2}}{1+\dfrac{p_{rise}}{\Delta p_{DandP}} - \dfrac{\Delta p_{fdowntoP}}{\Delta p_{DandP}}}. \qquad (3)$$

From the Reader-Harris/Gallagher (1998) Equation

$$\frac{\Delta p_{fdowntoP}}{\Delta p_{DtoP}} = \frac{2}{C_{DandP}} 0.031\left(M'_{2P} - 0.8\times M'_{2P}{}^{1.1} - (M'_{2\,flange} - 0.8\times M'_{2\,flange}{}^{1.1})\right)\beta^{1.3}, \quad (4)$$

where $M_2' = 2L_2'/(1-\beta)$ and L_2' is the quotient of the distance of the downstream tapping (or point P) from the downstream face of the orifice plate and the pipe diameter.

A reasonable result is obtained with point P 0.125D downstream of the plate.

As far as the data collected in this project are concerned this is almost equivalent to following the simpler model in [4], but the attraction of using the model here is that it is more consistent when different pipe diameters are used. It also puts the downstream pressure tapping at a smaller value of M_2' for smaller β.

There is also an additional loss term which should be included. It is reasonable to suppose that there is a loss equivalent to between 0 and 7D of pipe and that, given that the recirculation zone is shorter for larger β, the loss (in terms of number of pipe diameters) should increase with β. The effect of static hole error will be small compared with this pressure loss and is not included explicitly. Then a reasonable equation is:

$$\frac{\Delta\varpi_{meas}}{\Delta p_{flange}} = \frac{\dfrac{p_{rise}}{\Delta p_{DandP}} + \dfrac{\sqrt{1-\beta^4(1-C_{DandP}{}^2)} - C_{DandP}\beta^2}{\sqrt{1-\beta^4(1-C_{DandP}{}^2)} + C_{DandP}\beta^2}}{1+\dfrac{p_{rise}}{\Delta p_{DandP}} - \dfrac{\Delta p_{fdowntoP}}{\Delta p_{DandP}}} + \frac{a\beta^{b+4}C_{DandP}{}^2}{1-\beta^4}, \quad (5a)$$

where C_{DandP} is determined from the Reader-Harris/Gallagher (1998) Equation with L_1 = 1 and L_2' = 0.125. L_1 is the quotient of the distance of the upstream tapping from the upstream face of the orifice plate and the pipe diameter.

a = 0.05625 and b = 1, which correspond to a loss due to a pipe of length 4.5$\beta\,D$ of friction factor λ = 0.0125, have been used.

$$\frac{p_{rise}}{\Delta p_{DandP}} = \frac{2}{C_{DandP}} 1.033\left(0.123e^{-7L_1} - 0.080e^{-10L_1} - 0.00011\right)\frac{\beta^4}{1-\beta^4} \qquad (5b)$$

$$\frac{\Delta p_{fdowntoP}}{\Delta p_{DtoP}} = \frac{2}{C_{DandP}} 0.031\left(M'_{2P} - 0.8\times M'_{2P}{}^{1.1} - (M'_2 - 0.8\times M'_2{}^{1.1})\right)\beta^{1.3}. \qquad (5c)$$

In Equations (5b) and (5c) L_1 and M_2' are based on the actual tapping positions and $M_2'{}_P$ on L_2' = 0.125.

Using this approach the difference in the measured pressure loss ratio (using flange and 6*D* tappings) from the theoretical baseline in Equation (5) is determined and shown in Figures 25 to 28.

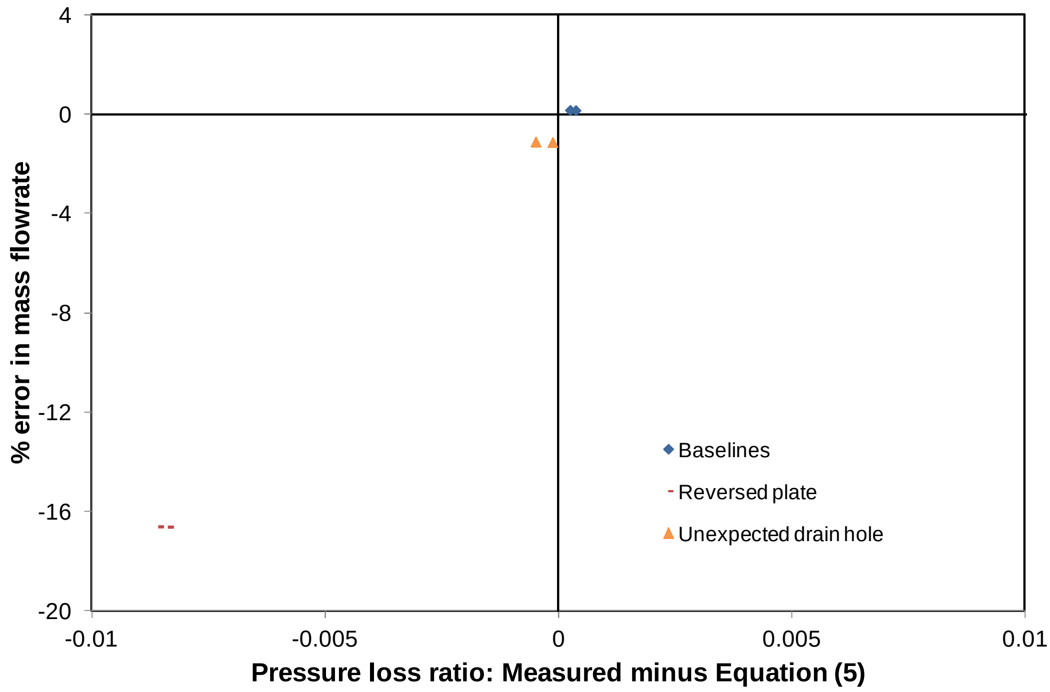

Figure 25 Error in mass flowrate using Reader-Harris/Gallagher (1998) Equation vs Deviation in measured pressure loss ratio from Equation (5): β = 0.2 orifice plate

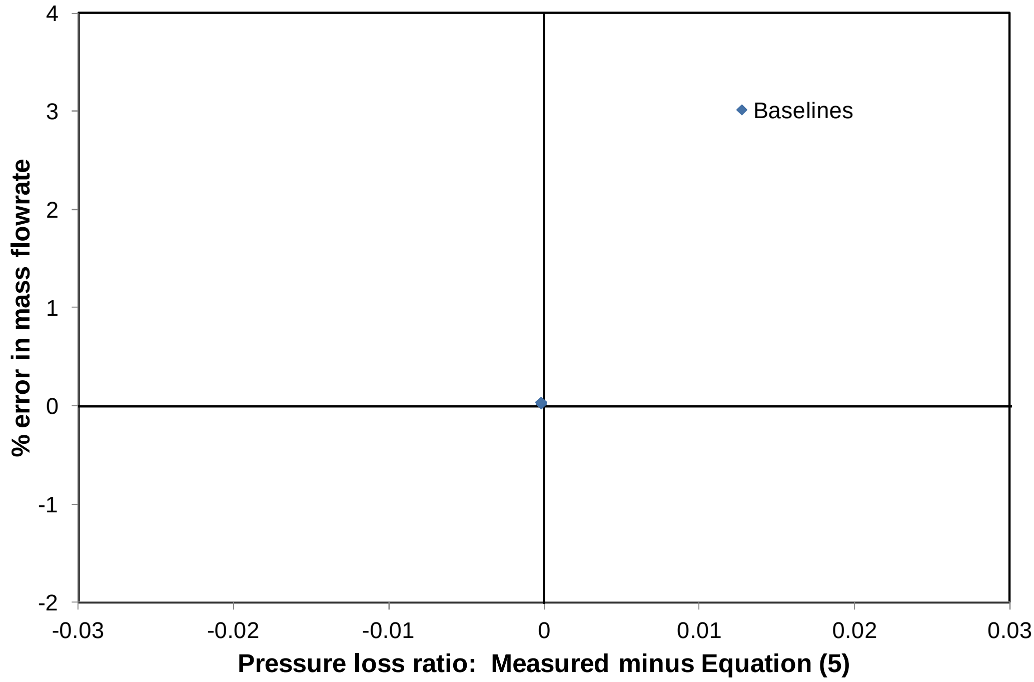

Figure 26 Error in mass flowrate using Reader-Harris/Gallagher (1998) Equation vs Deviation in measured pressure loss ratio from Equation (5): β = 0.4 orifice plate

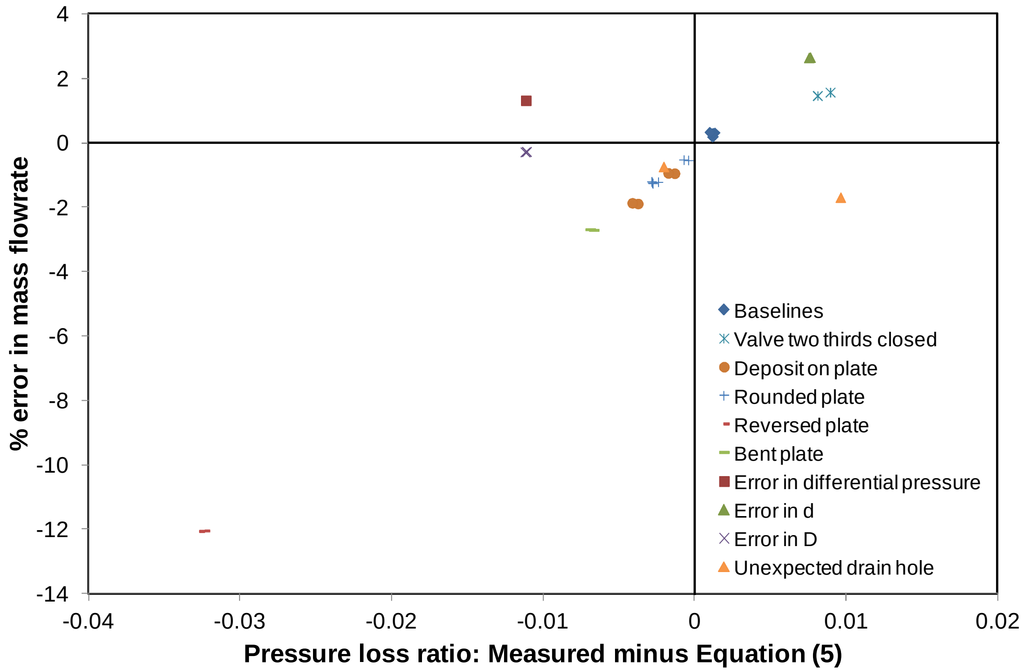

Figure 27 Error in mass flowrate using Reader-Harris/Gallagher (1998) Equation vs Deviation in measured pressure loss ratio from Equation (5): β = 0.6 orifice plate

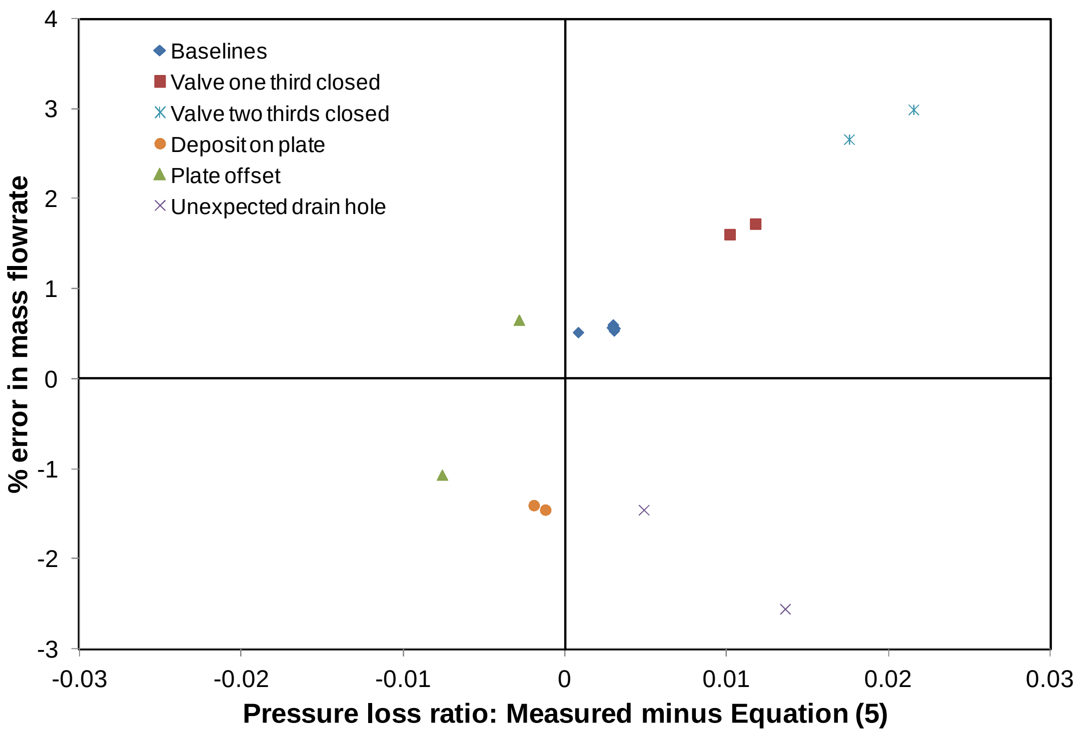

Figure 28 Error in mass flowrate using Reader-Harris/Gallagher (1998) Equation vs Deviation in measured pressure loss ratio from Equation (5): β = 0.75 orifice plate

Figures 25 to 28 show that Equation (5) performs well. To give more confidence in Equation (5) it would be necessary to have more data on pressure losses to analyse. More data would give a much clearer view of what is a significant deviation of measured PLR from that given by Equation (5).

In Figure 29 Equation (5) is compared with the data collected by CEESI as part of their Wet Gas JIP. These data were collected in 4″ (100 mm) diameter pipe with flange tappings and a tapping 6*D* downstream. The data from [6] have been used here although the data appear to be also presented in [2] but with different values.

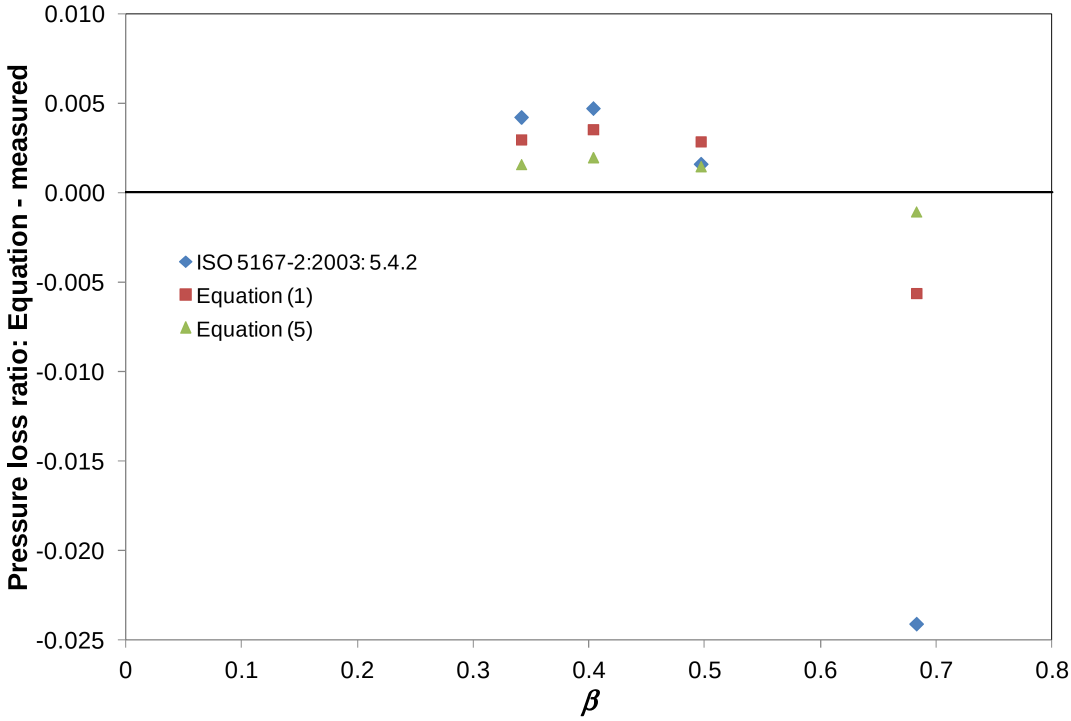

Figure 29 Different equations compared with measured values of measured pressure loss ratio in 4″ (100 mm) diameter pipe [6]

The data in Figure 29 suggest that the correction to the equation for PLR to reflect the use of flange tappings with a 6*D* downstream tapping is small but not negligible at values of β up to 0.5, whereas as β increases above 0.5 the correction must be considered necessary if a theoretical baseline PLR is to be used.

The applicability of Equation (1) was also discussed by Steven et al. [7]: they presented a large quantity of PLR data and showed that Equation (1) fitted their data well for $\beta \leq 0.55$ but that a bias was observed for $\beta > 0.55$. Steven et al. obtained an empirical equation for PLR as a function of β for use for $\beta > 0.55$ and applicable across the range of their data.

6 CONCLUSIONS

The work in this project has shown that an additional downstream pressure tapping can be used to provide a powerful diagnostic method. A shift in discharge coefficient due to a fault can in many cases be spotted from a change in the measured pressure loss ratio and in some cases the value of the shift estimated.

The simple diagnostic of summing the measured pressure loss and the measured pressure recovery and comparing with the measured differential pressure is surprisingly powerful.

When a measured baseline is available the 'Prognosis' method works very well in discerning problems. However, it is desirable to be able to use this sytem when no measured baseline is available: a simple application of equation (7) in 5.4.1 of ISO 5167-2:2003 is unsatisfactory for large β when flange tappings are used.

When a measured baseline or an appropriate empirical prediction is not available an improved diagnostic calculation based on the work in [4] gives much better results.

When a measured baseline is not available the quality of the downstream pipe in which the pressure loss ratio is measured is of great importance. Apparently small deviations can affect the measured pressure loss ratio very significantly. Spark eroding the tappings (to avoid burrs or rounded edges) is not sufficient.

If it were desired not only to predict the presence or absence of a fault but the value of the shift in discharge coefficient the use of an additional tapping *D* upstream of the orifice plate would be helpful. Then the ratio of the shift in discharge coefficient to the pressure loss ratio would not depend on whether the fault is at the orifice plate or upstream of it.

7 RECOMMENDATIONS FOR FURTHER WORK

Further work to determine measured pressure loss ratios in a wide variety of pipes of different diameter is required. The need is to know how well the measured pressure loss ratio can be predicted in good flow conditions, so that errors of 1% or less can be spotted.

8 NOTATION

C	discharge coefficient
C_{DandP}	discharge coefficient using tappings *D* upstream and at P downstream
D	pipe diameter
d	orifice diameter
L_1	quotient of the distance of the upstream tapping from the upstream face of the orifice plate and the pipe diameter
L_2'	quotient of the distance of the downstream tapping from the downstream face of the orifice plate and the pipe diameter
M_2'	quotient of the distance of the downstream tapping from the downstream face of the orifice plate and the dam height: $M_2'=2L_2'/(1-\beta)$
PLR	pressure loss ratio (see 3.1)
p_{rise}	pressure rise from *D* upstream to the the upstream flange tapping
v	mean velocity in the pipe
β	diameter ratio
Δp_{DandP}	differential pressure using tappings *D* upstream and at P downstream

$\Delta p_{fdowntoP}$ pressure drop from the downstream flange tapping to the point P

Δp_{flange} differential pressure using flange tappings

$\Delta \varpi$ pressure loss from the upstream *D* tapping to 6*D* downstream

$\Delta \varpi_{meas}$ pressure loss from the upstream flange tapping to 6*D* downstream

λ friction factor

9 ACKNOWLEDGMENTS

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

The authors are grateful for funding from the Innovation Funding Initiative (IFI).

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