ORIFICE PLATE METER DIAGNOSTICS

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1. Introduction

Orifice plate meters are popular for being relatively simple, reliable and inexpensive. Their principles of operation are relatively easily understood. However, traditionally there has been no orifice meter self diagnostic capabilities. In 2008 & 2009 a generic Differential Pressure (DP) meter self diagnostic methodology [1,2] was proposed. In this paper these diagnostic principles are applied to orifice meters and proven with experimental test results. The diagnostic results are presented in a simple graphical form designed for easy use in the field by the meter operator.

2. The orifice meter classical and self-diagnostic operating principles

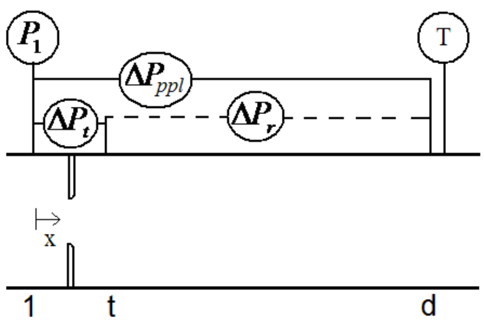

Fig 1. Orifice meter with instrumentation sketch.

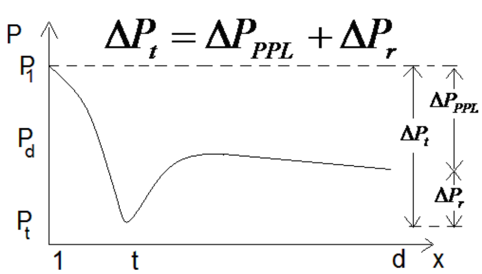

Fig 2. Simplified pressure fluctuation.

Figures 1 & 2 show an orifice meter with instrumentation sketch and the (simplified) pressure fluctuation through the meter body. Traditional orifice meters read the inlet pressure (P_1) from a pressure port (1) directly upstream of the plate, and the differential pressure (ΔP_t) between the inlet pressure port and a pressure port positioned directly downstream of the plate at a point of low pressure (t). The temperature (T) is also usually measured downstream of the meter. Note that the orifice meter in Figure 1 has a third pressure tap (d) further downstream of the plate. This addition to the traditional orifice meter design allows the measurement of two extra DP's. That is, the differential pressure between the downstream (d) and the low (t) pressure taps (or "recovered" DP, ΔP_r) and the differential pressure between the inlet (1) and the downstream (d) pressure taps (i.e. the permanent pressure loss, ΔP_{PPL}, sometimes called the "PPL" or "total head loss").

Adding the recovered DP to the PPL must give the traditional differential pressure (equation 1). Hence, in order to obtain three DP's, only two DP transmitters are required.

$$\Delta P_t = \Delta P_r + \Delta P_{PPL} \quad \text{--- (1)}$$

Traditional Flow Equation:

$$\dot{m}_t = EA_t Y C_d \sqrt{2\rho\Delta P_t} \text{ , uncertainty} \pm x\% \quad \text{--(2)}$$

Expansion Flow Equation:

$$\dot{m}_r = EA_t K_r \sqrt{2\rho\Delta P_r} \text{ , uncertainty} \pm y\% \quad \text{--(3)}$$

PPL Flow Equation:

$$\dot{m}_{ppl} = AK_{PPL} \sqrt{2\rho\Delta P_{PPL}} \text{ ,uncertainty} \pm z\% \quad \text{--(4)}$$

Each of these three DP's can be used to independently predict the flow rate. Equations 1 to 3 show the three flow rate calculations for these three DP's. Note that $\dot{m}_t$, $\dot{m}_r$ & $\dot{m}_{PPL}$ are the mass flow rate predictions of the actual flow when using the traditional, recovered and PPL DP's respectively. The terms E, A & A_t are constant geometry terms and ρ is the fluid density. Y is the expansion factor that accounts for any gas density variation through the meter. (For liquids Y =1.) The terms C_d, K_r & K_{PPL} represent the flow coefficients required by each meter calculation. They are the discharge, expansion and PPL coefficients respectively. These flow coefficients can either be set to a constant value or for more precision they can be related to the flows Reynolds number.

Traditionally, an orifice meter run is seen as a single flow meter. However, it has now been shown that <u>every orifice meter run is in effect three flow meters in series</u>. As there are three flow rate predictions for the same flow through the same meter run there is the potential to compare these flow rate predictions and hence have a diagnostic system.

Naturally, all three flow rate predictions have individual uncertainty ratings (say x%, y% & z% as shown in equations 2 through 4). Hence, even if an orifice meter is operating correctly, no two flow predictions would match *precisely*. However, a correctly operating orifice meter will produce flow predictions that are very close to each other. An operator can therefore choose an acceptable maximum difference between any two of these flow rate predictions.

Let us denote the **actual** difference between the traditional & PPL meter flow predictions as "$\psi\%$". Now let us denote the maximum **allowable** difference between the traditional & PPL meters flow predictions as "$\phi\%$". If the actual difference is less than the allowable difference (i.e. $\psi\%/\phi\% \le 1$) then no meter malfunction is found. However, if the actual difference is more than the allowable difference (i.e. $\psi\%/\phi\% > 1$) then a meter malfunction has been found.

Let us denote the **actual** difference between the traditional & expansion meter flow predictions as "$\lambda\%$". Now let us denote the maximum **allowable** difference between the traditional & expansion meters flow predictions as "$\xi\%$". If the actual difference is less than the allowable difference (i.e. $\lambda\%/\xi\% \le 1$) then no meter malfunction is found. However, if the actual difference is more than the allowable difference (i.e. $\lambda\%/\xi\% > 1$) then a meter malfunction has been found.

Let us denote the **actual** difference between the PPL & expansion meter flow predictions as "$\chi\%$". Now let us denote the maximum **allowable** difference between the traditional & expansion meters flow predictions as "$\upsilon\%$". If the actual difference is less than the allowable difference (i.e. $\chi\%/\upsilon\% \le 1$) then no meter malfunction is found. However, if the actual difference is more than the allowable difference (i.e. $\chi\%/\upsilon\% > 1$) then a meter malfunction has been found.

This diagnostic methodology uses the three individual DP's to independently predict the flow rate and then compares these results. In effect, the individual DP's are therefore being directly compared.

It is possible to take a different diagnostic approach. The **P**ressure **L**oss **R**atio (or "PLR") is the ratio of the PPL to the traditional DP. For a correctly operating orifice meter the PLR is a known value. ISO 5167 [3] predicts the orifice meter PLR for any single phase flow condition.

$\frac{\Delta P_r}{\Delta P_t} + \frac{\Delta P_{PPL}}{\Delta P_t} = 1$ -- (1a) where $\frac{\Delta P_{PPL}}{\Delta P_t}$ is the PLR.

By re-writing equation 1 as equation 1a, we see that as the PLR is a set predictable value then both the **P**ressure **R**ecovery **R**atio or "PRR", (i.e. the ratio of the recovered DP to traditional DP) and the **R**ecovered DP to **P**PL **R**atio, or "RPR" must also be set predictable values. That is, all three DP ratios produced by a correctly operating orifice meter are predictable, i.e. known. An operator can assign allowable uncertainties to these three DP ratio predictions:

PPL to Traditional DP ratio (PLR):
$(\Delta P_{PPL}/\Delta P_t)_{cal}$, uncertainty ± a%
Recovered to Traditional DP ratio (PRR):
$(\Delta P_r/\Delta P_t)_{cal}$, uncertainty ± b%
Recovered to PPL DP ratio (RPR):
$(\Delta P_r/\Delta P_{PPL})_{cal}$, uncertainty ± c%

Here then is another method of using the three DP's to check an orifice meters health. Actual DP ratios found in service can be compared to the known correct operational values.

Let us denote the **actual** difference between the PLR as found and the correct operation PLR value as α%. Now let us denote the maximum allowable difference between these values as a%. If the actual difference is less than the allowable difference (i.e. $\alpha\%/a\% \le 1$) then no meter malfunction is found. However, if the actual difference is more than the allowable difference (i.e. $\alpha\%/a\% > 1$) then a meter malfunction has been found.

Let us denote the **actual** difference between the PRR as found and the correct operation PRR value as γ%. Now let us denote the maximum allowable difference between these values as $b\%$. If the actual difference is less than the allowable difference (i.e. $\gamma\%/b\% \le 1$) then no meter malfunction is found. However, if the actual difference is more than the allowable difference (i.e. $\gamma\%/b\% > 1$) then a meter malfunction has been found.

Let us denote the **actual** difference between the RPR as found and the correct operation RPR value as $\eta\%$. Now let us denote the maximum allowable difference between these values as $c\%$. If the actual difference is less than the allowable difference (i.e. $\eta\%/c\% \le 1$) then no meter malfunction is found. However, if the actual difference is more than the allowable difference (i.e. $\eta\%/c\% > 1$) then a meter malfunction has been found.

Table 1 shows the six situations where these diagnostics will produce a meter malfunction warning. Note that each DP pair has two diagnostic methods associated with that DP pair. That is, for each DP pair, the two flow rate predictions can be compared to each other or the DP ratio can be compared to the set known correct value.

DP Pair	No Alarm	ALARM
ΔP_t & ΔP_{PPL}	$\psi\%/\phi\% \le 1$	$\psi\%/\phi\% > 1$
ΔP_t & ΔP_r	$\lambda\%/\xi\% \le 1$	$\lambda\%/\xi\% > 1$
ΔP_{PPL} & ΔP_r	$\chi\%/\upsilon\% \le 1$	$\chi\%/\upsilon\% > 1$
ΔP_t & ΔP_{PPL}	$\alpha\%/a\% \le 1$	$\alpha\%/a\% > 1$
ΔP_t & ΔP_r	$\gamma\%/b\% \le 1$	$\gamma\%/b\% > 1$
ΔP_{PPL} & ΔP_r	$\eta\%/c\% \le 1$	$\eta\%/c\% > 1$

Table 1. Potential diagnostic results.

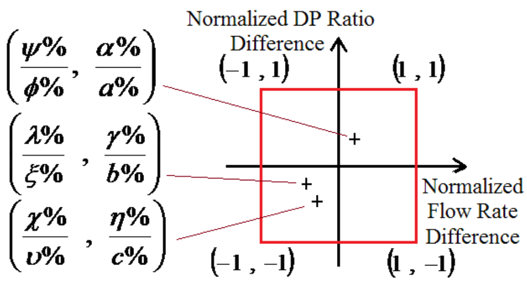

Fig 3. A diagnostic result plotted on the diagnostic box.

For practical use by typical operator personnel (who do not need know the details of the diagnostic method), a plot of these diagnostic results on a graph is simple and effective. Such a plot can be continually updated in real time on a control room screen or the data can archived for later analysis.

Figure 3 shows such a plot. The x-axis shows the flow rate comparison diagnostic result. The y-axis shows the DP ratio diagnostic result. A diagnostic box can be superimposed on the graph with corner co-ordinates: $(1,1)$, $(1,-1)$, $(-1,-1)$ & $(-1,1)$. On such a graph three meter diagnostic points can be plotted. These are $(\psi\%/\phi\%, \alpha\%/a\%)$ for the traditional & PPL DP pair, $(\lambda\%/\xi\%, \gamma\%/b\%)$ for the traditional & recovered DP pair and $(\chi\%/\upsilon\%, \eta\%/c\%)$ for the PPL & recovered DP pair. In such a plot, if all points are within or on the box then the meter operator sees no metering problem and the traditional meters flow rate prediction should be trusted. However, if one or more of the three points falls outside the NDB the meter operator has a visual indication that the meter is ***not*** operating correctly and that the meters traditional (or any) flow rate prediction cannot be trusted. The further from the NDB the points are, the more potential for significant meter error there is. Note that in this random theoretical example shown in Figure 3 all points are within the NDB indicating the meter is operating within the limits of normality, i.e. no metering problem is noted.

3. <u>Correctly operating orifice plate meter data</u>

An orifice meters discharge coefficient and PLR values are directly available from standards documents. These discharge coefficient and PLR statements allow the expansion coefficient, PPL coefficient, the PRR and the RPR to be directly derived from the standards (see Steven [1] for the derivations).

The standards give an uncertainty statement for the discharge coefficient. However, the other five parameters have not stated uncertainty in the standards. In order for this diagnostic method to operate all six of these parameters must have associated uncertainties assigned to them.

Fortunately, multiple tests of various geometry orifice meters with the downstream pressure port have shown that the full performance of orifice meters (i.e. downstream pressure port inclusive) is very reproducible. Hence, from multiple data sets it is possible to assign reasonable

Fig 4. Orifice fitting with natural gas flow.

Fig 5. Flange installed plate with air flow.

uncertainty statements to the expansion and PPL coefficients and the three DP ratios.

Three 4", 0.5 beta ratio flange tap orifice meter data sets were recorded at CEESI and analyzed by DP Diagnostics. The first was a natural gas flow test on an orifice fitting installed plate. In these tests only the traditional DP and PPL were read. The downstream pressure port is located at six diameters downstream of the back face of the plate as this is where ISO suggest DP recovery is complete. The recovered DP was derived by equation 1. Figure 4 shows a photograph of the test set up at CEESI. The other two data sets are from separate air flow, flange installed paddle plate, orifice meter tests carried out at CEESI in 2008 and 2009. The 2008 tests used Daniel plates. The 2009 tests use Yokogawa plates. These air tests both directly read all three DP's. Again the downstream pressure port was at six diameters downstream of the back face of the plate. Figure 5 shows these tests set up.

Tables 2, 3 & 4 shows the data range of these three "baseline" (i.e. correctly operating) orifice meter tests. Figure 6 shows the average constant value of the discharge coefficient, expansion coefficient and PPL coefficient from all three

Orifice Type & Fit	Daniel Orifice Fitting
No. of data points	112
Diameter	4.026"
Beta Ratio	0.4965 (single plate)
Pressure Range	13.1 < P (bar) < 87.0
DPt Range	10"WC< DPt <400"WC
DPr Range	10"WC <DPr < 106"WC
DPppl Range	10"WC <PPL < 293"WC
Reynolds No. Range	350 e3 < Re < 8.1e6

Table 2. Natural gas baseline data sets.

Orifice Type & Fit	Daniel Plate / Flange
No. of data points	44
Diameter	4.026"
Beta Ratio	0.4967 (multiple plates)
Pressure Range	15.0 < P (bar) < 30.0
DPt Range	15"WC< DPt < 385"WC
DPr Range	10"WC < DPr < 100"WC
DPppl Range	11"WC<PPL< 285"WC
Reynolds No. Range	300e3 < Re < 2.1e6

Table 3. 2008 air baseline data sets.

Orifice Type & Fit	Yokogawa Plate /Flange
No. of data points	124
Diameter	4.026"
Beta Ratio	0.4967 (multiple plates)
Pressure Range	14.9 < P (bar) < 30.1
DPt Range	15"WC< DPt < 376"WC
DPr Range	10"WC <DPr < 100"WC
DPppl Range	11"WC<PPL< 277"WC
Reynolds No. Range	317e3 < Re < 2.2e6

Table 4. 2009 air baseline data sets.

data sets analyzed together and the associated uncertainty values of the fit. Figure 7 shows the average constant value PLR, PRR & RPR from all three data sets analyzed together and the associated uncertainty values of the fit. Figures 6 & 7 show that all six parameters exist at relatively low uncertainty and that they are repeatable and reproducible. (Note that the sum of the PLR and PRR is not *quite* unity as required by equation 1a due to data uncertainty.) It has subsequently been shown by further testing, and by third party field trials, that these assigned uncertainty statements are reasonable.

After multiple orifice meter tests at test facilities and various field tests the uncertainty of these ISO 5167 derived orifice meter diagnostic are known. With an additional safety factor added (to guard against the diagnostic system producing false warnings) Table 5 shows the advised uncertainty values for each of the diagnostic parameters.

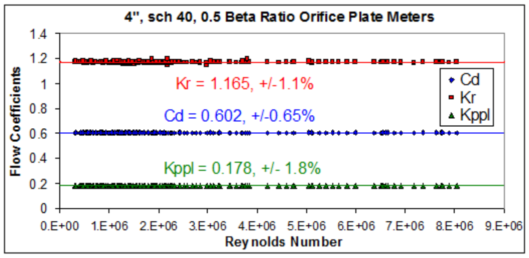

Fig 6. Combined 4", 0.5 beta ratio orifice plate meter flow coefficient results.

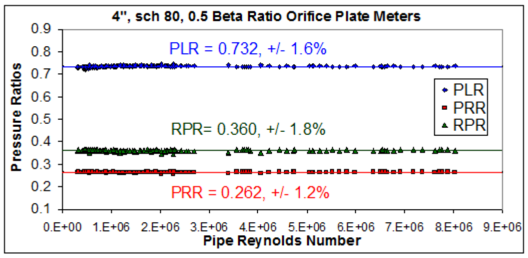

Fig 7. Combined 4", 0.5 beta ratio orifice plate meter DP ratio results.

Flow Coefficient	Uncertainty	DP Ratio	Uncertainty
Cd	1.0%	PLR	2.6%
Kr	2.0%	PRR	2.2%
Kppl	3.0%	RPR	4.0%

Table 5. Assigned Uncertainty Values

It may be noted that the discharge coefficient uncertainty is stated as 1.0%. However, the discharge coefficient uncertainty stated by ISO 5167 is 0.5%. This is an example of the addition of a safety factor. It should be understood that these diagnostics do not interfere in any way with the normal operation of the orifice meter. The meter will continue to have a discharge coefficient used for the primary flow measurement with an uncertainty of 0.5%. The assignment of a 1.0% uncertainty is solely for the separate use of the discharge coefficient in the diagnostics system, where the increase is solely to reduce the sensitivity of the diagnostic system to avoid false warnings.

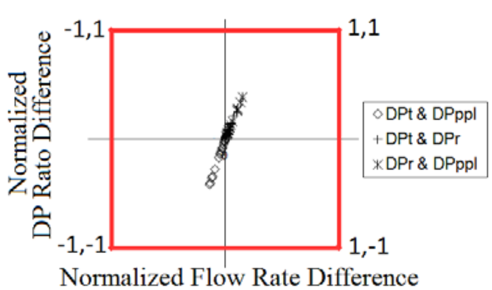

Fig 8. Correctly operating meter diagnostic results.

Figure 8 shows sample baseline data. The diagnostic plots from a correctly operating 4", 0.5 beta ratio orifice meter tested over a range of flow rates are shown. Note that each flow point recorded will produce three DP's and therefore three points on the graph. Therefore, at any one time in actual use the diagnostic system shows three points only on the graph. However, in Figure 8 for educational purposes massed data is shown, i.e. three points for each of the flow rates tested. The points are all inside the box thereby indicating correctly that the meter is operating correctly.

This result in itself could be seen as trivial as this orifice meter was carefully set up by CEESI (a test laboratory) with a reference meter to double check its correct performance. However, the non-trivial results are from orifice meters deliberately tested when malfunctioning for a variety of reasons. Examples of such tests are now given.

4. Incorrectly operating orifice plate meter data

There are many common orifice meter field problems. A few examples are now discussed with the associated diagnostic system response shown. The capability of the diagnostic system is not limited to just these malfunctions. The system will warn the operator of a meter malfunction for many other malfunction events. All orifice meter diagnostic results shown in the examples use ISO parameter predictions with uncertainties shown in Table 5.

4.1. Incorrect Entry of Inlet Diameter

Modern orifice meter flow rate calculations are processed by flow computers. The flow computer requires that the meter operator keypad enter certain pieces of information about the meter prior to operation. Once the meter is in operation, the flow computer will be supplied the traditional DP produced by the flow through the meter. It then combines this DP and keypad entered information to produce a flow rate prediction. Therefore, if the information entered into the flow computer is erroneous then an error in the flow rate prediction will occur.

One piece of information that must be keypad entered into the flow computer is the inlet diameter of the meter. If the operator enters the wrong inlet diameter then the flow computer combines the read DP and this erroneous keypad entered information into an erroneous flow rate prediction. The orifice meter still reads a traditional DP produced by the flow, but the flow rate prediction is dependent on the keypad entry information being correct. However, the traditional orifice meter system has no method of checking human error in the keypad entered information. Traditionally the operator must simply assume (or hope) that the information is correct as there was no orifice meter self-diagnostic check to identify such an error.

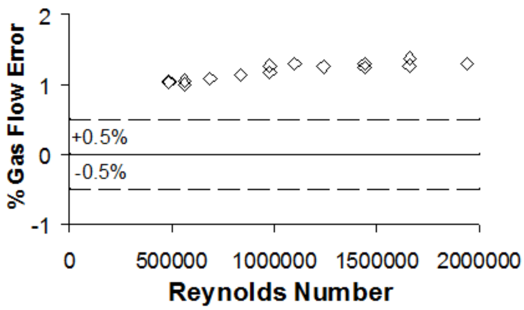

Fig 9. An inlet diameter flow prediction error.

Figure 9 indicates the error induced if sample baseline data in section 3 was given the wrong inlet diameter. Instead of the correct 4", sch 40 (4.026") inlet diameter from the 2009 baseline tests being used 4" sch 80 (3.826") was entered. The resulting error was a positive bias of approximately +1.5%. Figure 10 shows that the resulting diagnostic plot. (Note that in this paper the entire data set of all the points recorded are shown in one plot – in actual operation only three points would exist at any given moment.) Clearly, the plot correctly shows that the meter has a problem. This is the first orifice meter diagnostic system to show a flow rate prediction error when there is a diameter keypad error.

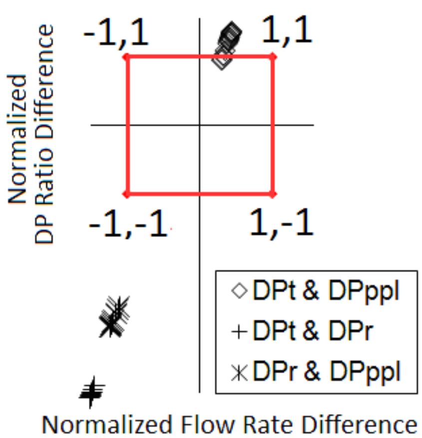

Fig 10. Inlet diameter error diagnostics result.

4.2. Incorrect Entry of Orifice Diameter

The flow computer also requires that the orifice diameter be keypad entered. If the operator enters the wrong orifice diameter then the flow computer combines the read DP and this erroneous keypad entered information into an erroneous flow rate prediction. Again, the orifice meter still reads a traditional DP produced by the flow, but the flow rate prediction is dependent on the keypad entry information being correct. With no traditional method of checking keypad entries traditionally the operator must simply assume (or hope) that the information is correct as there was no orifice meter self-diagnostic check to identify such an error.

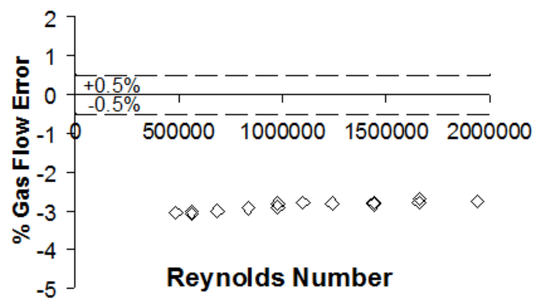

Fig 11. An orifice diameter flow prediction error.

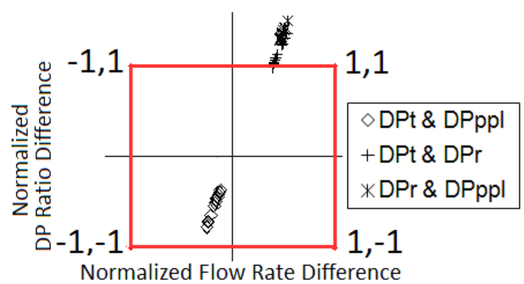

Fig 12. Orifice diameter error diagnostics result.

Figure 11 indicates the error induced if the sample baseline data discussed in section 3 is given the wrong orifice diameter. Instead of the correct 1.999" orifice diameter being entered an incorrect 1.970" orifice diameter is entered. The resulting error is a negative bias of approximately -2.5%. Figure 12 shows that the diagnostic plot that would be shown on the operators control room screen (although again in actual application only three points exist at any given moment). Note it only takes one of the three points to be out with the NDB for a problem to be identified. Clearly, the recovered DP & PPL pair identify correctly that the meter has a problem. This is the first orifice meter diagnostic system to show a flow rate prediction error when there is an orifice diameter error.

4.3. Reversed orifice plate installation

Orifice plates are often installed erroneously in the reverse (or "backwards") direction to the flow. Such an installation changes the effective geometry of the orifice plate seen by the flow. This in turn changes the DP produced for any given flow condition from that which would have been produced if the plate was correctly installed. Once the meter is in operation, the flow calculation will be supplied the DP produced by the flow through the reversed orifice plate. It then combines this DP and keypad entered information to produce a flow rate prediction. However, one of the pieces of required keypad entered information is the orifice meters discharge coefficient. The discharge coefficient information is supplied via the standards documents. However, the standards discharge coefficient statements are only valid for the case of a properly installed plate. A reversed orifice plate will produce a distinctly different discharge coefficient. Therefore, when the flow calculation receives the DP produced by the reversed plate and uses the keypad entered discharge coefficient for a correctly installed plate the flow rate prediction has an error. If an orifice plate is installed backwards there are no traditional internal meter diagnostics to indicate that the meter is operating in error. Traditionally the meter operator must assume (i.e. hope) that the plate is installed correctly.

Table 6 shows the test conditions when one of the 4", sch 40, 0.5 beta ratio paddle plate orifice meters was tested at CEESI deliberately installed backwards.

Pressure	15 Bar
Traditional, DPt	14"WC < DPt < 327"WC
Expansion, DPr	5"WC < DPr < 98"WC
PPL, DPppl	10"WC<DPppl <229"WC
Reynolds Number	367e3 < Re < 1.66e6

Table 6. Backwards plate test data range.

Figure 13 shows the repeatable traditional flow rate prediction error when a 0.5 beta ratio orifice meter has the plate installed backwards. A negative bias of approximately -15% is produced.

The diagnostic data plot shown as Figure 14 very clearly shows that the meter has a problem. In this case as the problem is a precise geometry issue the precise pattern on the diagnostic plot indicates to the user the problem is most likely the 0.5 beta ratio plate is installed backwards.

This is the first orifice meter diagnostic system to show a flow rate prediction error when the orifice plate is installed backwards.

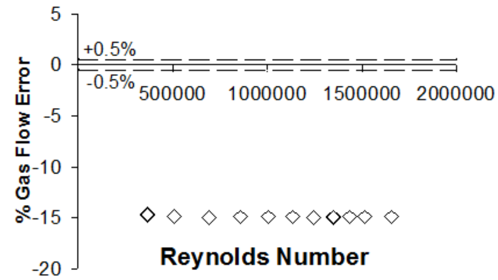

Fig 13. A backwards installed orifice plate error.

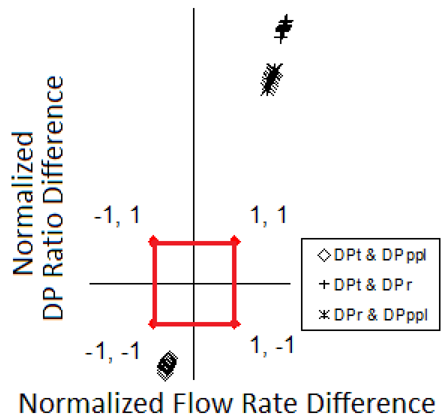

Fig 14. Backwards plate diagnostics result.

4.4. A moderately buckled (or "warped") plate

Adverse flow conditions can damage orifice plates. A buckled plate changes the effective geometry of the orifice plate seen by the flow. This in turn changes the DP produced for any given flow condition from that which would have been produced if the plate was undamaged. The flow calculation will be supplied this DP produced by the flow through the buckled orifice plate. It then combines this DP and keypad entered information to produce a flow rate prediction. However, the keypad entered discharge coefficient is only valid for when the plate is undamaged. A buckled orifice plate will produce a different discharge coefficient. Therefore, when the flow calculation receives the DP produced by the buckled plate and uses the keypad entered discharge coefficient for a correctly installed undamaged plate the flow rate prediction has an error.

If an orifice plate is buckled there are no traditional internal meter diagnostics to indicate that the meter is operating in error. Traditionally the meter operator must assume (i.e. hope) that the plate is undamaged.

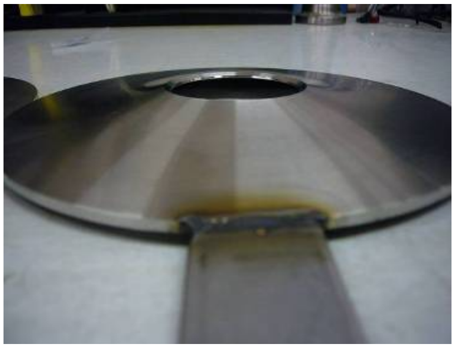

Fig 15. Moderately buckled orifice plate.

A moderately buckled 4”, 0.5 beta ratio paddle plate was tested at CEESI. Figure 15 shows the buckled plate. Note that as a paddle plate the compression effect during the tightening of the flange bolts reduced the buckle level seen here. Table 7 shows the test data ranges.

Pressures	15 & 30Bar
Traditional, DPt	14”WC <DPt< 352”WC
Expansion, DPr	5”WC <DPr< 99”WC
PPL, DPppl	10”WC<DPppl<254”WC
Reynolds No. Range	331e3 < Re < 2.2e6

Table 7. Buckled plate test data range.

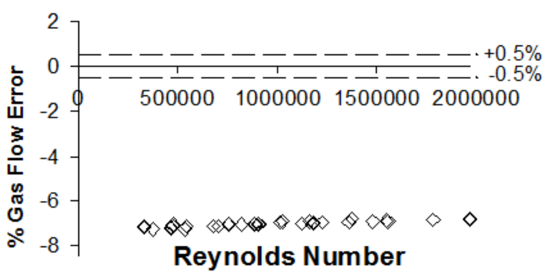

Fig 16. A buckled orifice plate meter error.

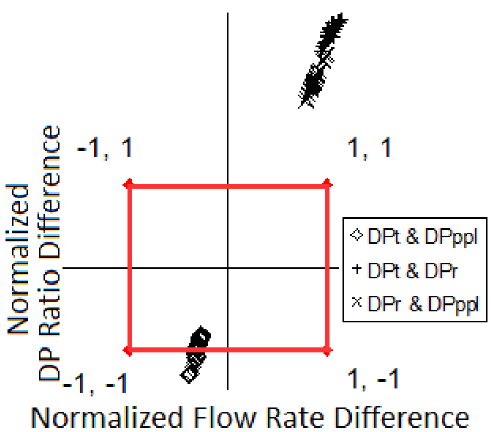

Fig 17. Buckled orifice plate meter diagnostics result.

Figure 16 shows the traditional flow rate prediction error due to the plate buckling. The buckle produces an approximate negative bias of -7%. Like all the data discussed in this paper the pressure had no effect on the results and the results were very repeatable. Figure 17 shows the buckled plate data set diagnostic plot indicating that the meter has a significant problem. This is the first orifice meter diagnostic system to show a flow rate prediction error when the orifice plate is buckled.

4.5. Worn leading orifice edge

Orifice plate sharp edges can be worn leading to flow measurement errors. A worn edge on an orifice plate changes the effective geometry of the orifice plate seen by the flow. This in turn changes the DP produced for any given flow condition from that which would have been produced if the plates edges remained sharp. The flow calculation will be supplied this DP produced by the flow through the worn edge orifice plate. It then combines this DP and keypad entered information to produce a flow rate prediction. However, the keypad entered discharge coefficient is only valid for when the plate is undamaged. A worn edge plate will produce a different discharge coefficient. Therefore, when the flow calculation receives the DP produced by the worn edge plate and uses the keypad entered discharge coefficient for a correctly installed undamaged plate the flow rate prediction has an error.

If an orifice plate has a worn edge there are no traditional internal meter diagnostics to indicate that the meter is operating in error. Traditionally the meter operator must assume (i.e. hope) that the plate is undamaged.

Fig 18. Chamfered (0.02”) orifice edge.

DP Diagnostics tested various levels of wear on the plate edge. It was found that it took a surprisingly large amount of wear to produce a significant flow rate prediction error. Figure 18 shows a 4”, 0.5 beta ratio paddle plate with a

0.02” chamfer on the orifice edge. Table 8 shows the test data ranges.

Pressures	15 & 30 Bar
Traditional, DPt	14”WC <DPt< 359”WC
Expansion, DPr	4”WC <DPr< 99”WC
PPL, DPppl	10”WC<DPppl< 256”WC
Reynolds Number	35.2e4 < Re < 2.15e6

Table 8. Worn orifice plate edge test data range.

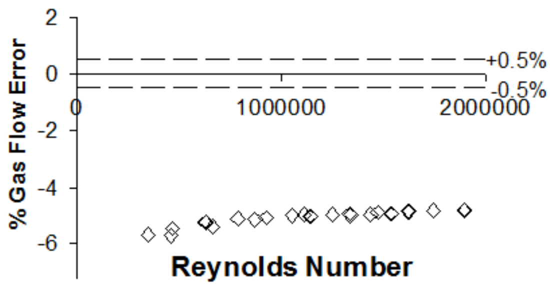

Fig 19. A worn edge orifice plate meter error.

Figure 19 shows the traditional flow rate prediction error due to the orifice edge wear. The wear produces an approximate negative bias of -5%. Figure 20 shows the “worn” plate diagnostic result indicating that the orifice meter has a significant problem. This is the first orifice meter diagnostic system to show a flow rate prediction error when the orifice plate edge is worn.

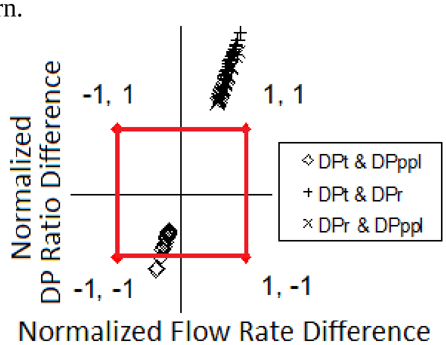

Fig 20. Worn edge orifice plate meter diagnostic results.

4.6. <u>Contaminated orifice plates</u>

Contaminates can deposit on plates leading to orifice meter flow rate prediction errors. Contamination on an orifice plate changes the effective geometry of the orifice plate seen by the flow. This in turn changes the DP produced for any given flow condition from that which would have been produced if the plate was clean. The flow calculation will be supplied this DP produced by the flow through the contaminated orifice plate. It then combines this DP and keypad entered information to produce a flow rate prediction. However, the keypad entered discharge coefficient is only valid for when the plate is uncontaminated. A contaminated orifice plate will produce a different discharge coefficient. Therefore, when the flow calculation receives the DP produced by the contaminated plate and uses the keypad entered discharge coefficient for a clean plate the flow rate prediction has an error.

If an orifice plate is contaminated there are no traditional internal meter diagnostics to indicate that the meter is operating in error. Traditionally the meter operator must assume (i.e. hope) that the plate is clean.

Fig 21. A heavily contaminated orifice plate.

Pressures	15 & 30 Bar
Traditional, DPt	17”WC <DPt< 368”WC
Expansion, DPr	4”WC <DPr< 99”WC
PPL, DPppl	12”WC<DPppl< 265”WC
Reynolds Number	34.6e4 < Re < 2.15e6

Table 9. Contaminated plate test data range.

DP Diagnostics tested at CEESI various levels of contamination on the plate. Again, as with the worn edge example, it was found that it took a surprising large amount of contamination to produce a significant flow rate prediction error. The contaminated plate was heavily painted (on the upstream side only) and then large salt granules embedded in the paint to produce an extremely rough surface. Figure 21 shows a 4”, 0.5 beta ratio paddle plate with this upstream surface contamination. Table 9 shows the test data ranges.

Figure 22 shows the traditional flow rate prediction error due to this plate contamination. The contamination produces an approximate negative bias of -3.5%. Figure 23 shows the contaminated plate diagnostic results. The recovered and traditional DP pair data points are all out with the diagnostic box indicating that the orifice meter has a problem. This is the first orifice meter diagnostic system to show a flow rate prediction error when the orifice plate is contaminated.

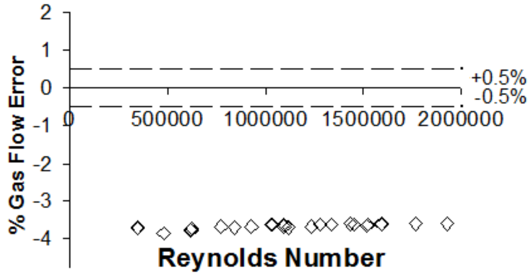

Fig 22. A heavily contaminated plate meter error.

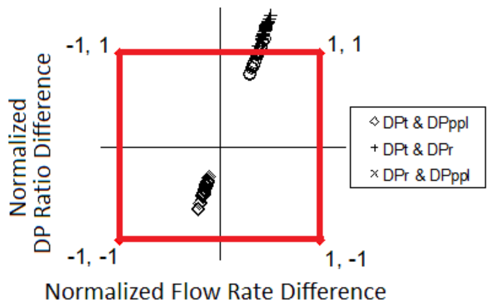

Fig 23. Heavily contaminated plate diagnostic results.

4.7. <u>Orifice plate meter installation effects</u>

The orifice meter standards state installation requirements. If an orifice meter is installed too close to pipe components, or if loose debris is accidentally deposited upstream of the meter or a flow conditioner is partially blocked, the disturbances to the flow profile entering the meter can cause flow measurement errors. Such disturbed flow through an orifice plate changes the meters performance. Disturbed flow through an orifice meter produces a different traditional DP at any given flow condition than undisturbed flow. The flow calculation will be supplied this DP produced by the disturbed flow. It then combines this DP and keypad entered information to produce a flow rate prediction. However, the keypad entered discharge coefficient is only valid for when the flow is undisturbed. A disturbed flow will produce a different discharge coefficient through any given orifice meter geometry. Therefore, when the flow calculation receives the DP produced by the disturbed flow and uses the keypad entered discharge coefficient for an undisturbed the flow rate prediction has an error.

If the inlet flow to an orifice plate is disturbed there are no traditional internal meter diagnostics to indicate that the meter is operating in error. Traditionally the meter operator must assume (i.e. hope) that the flow is not disturbed.

DP Diagnostics installed at CEESI a half moon orifice plate (HMOP) at 2D upstream of the meter to seriously disrupt the flow into a 4", 0.5 beta ratio orifice meter.

Pressures	15 Bar
Traditional, DPt	16"WC <DPt< 378"WC
Expansion, DPr	4"WC <DPppl< 98"WC
PPL, DPppl	11"WC <DPr< 281"WC
Reynolds No. Range	323e3 < Re < 1.52e6

Table 10. HMOP 2D upstream test data range

Table 10 shows the test data ranges. Figure 24 shows the traditional flow rate prediction error due to the disturbed flow profile. The effect is an approximate negative bias of -5.5%. Figure 25 shows the disturbed flow diagnostic results indicating that the orifice meter has a significant problem. This is the first orifice meter diagnostic system to show a flow rate prediction error when the flow is disturbed entering the orifice meter.

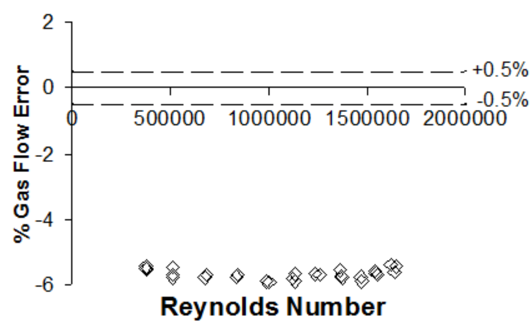

Fig 24. A velocity profile induced meter error.

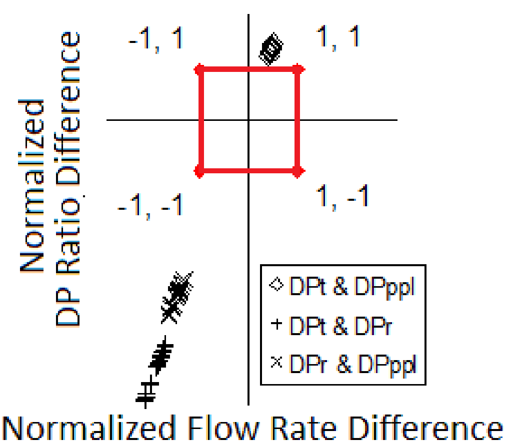

Fig 25. Disturbed velocity profile diagnostic results.

4.8. Wet gas flows and orifice plate meters

Often flows assumed to be single phase gas flows are actually wet gas flows. That is, unbeknown to the operator the gas has entrained liquids. This wet gas flow condition will induce a bias on an orifice meters gas flow rate prediction. Wet gas flow through an orifice meter produces a different (typically higher) traditional DP than if the gas flowed alone. The single phase flow calculation will be supplied this DP produced by the wet gas flow. It then combines this DP and keypad entered information to produce a flow rate prediction. However, the keypad entered discharge coefficient is only valid for single phase flow. Therefore, when the flow calculation receives the DP produced by the wet gas flow and uses the keypad entered discharge coefficient for a single phase flow the flow rate prediction has an error.

If wet gas flow is flowing through an orifice plate there are no traditional internal meter diagnostics to indicate that the meter is operating in error. Traditionally the meter operator must assume (i.e. hope) that the flow is not wet.

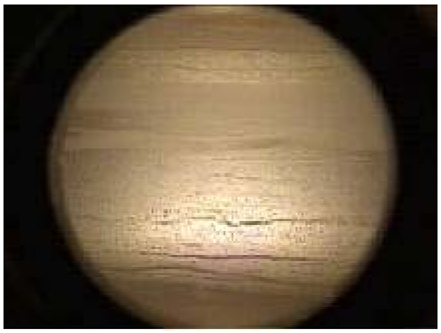

Fig 26. CEESI wet gas view port of wet gas flow upstream of orifice meter.

DP Diagnostics received wet gas flow orifice meter data from CEESI's wet natural gas flow loop. Figure 4 shows the set up. In this example the traditional DP and PPL were read directly. The recovered DP was inferred via equation 1. The data point had a pressure of 42.6 bar, a temperature of 305K, a gas density of 32 kg/m^3 and an actual gas flow rate of 3.3 kg/s. However, a light hydrocarbon liquid of density 731 kg/m^3 also flowed with the natural gas at a rate of 0.395 kg/s. This is a GVF of 98.9%. Approximately 1% of the total volume flow was liquid. Figure 26 shows a still from a wet gas video recorded from a CEESI view port located upstream of the meter during this test.

The orifice meter predicted the gas flow rate to be 3.43 kg/s, i.e. there was a positive gas flow rate bias (or an over-reading) of approximately 4%. Figure 27 shows this wet gas flow diagnostic result indicating that the orifice meter has a significant problem. This is the first orifice meter diagnostic system to show a flow rate prediction error when the flow is wet.

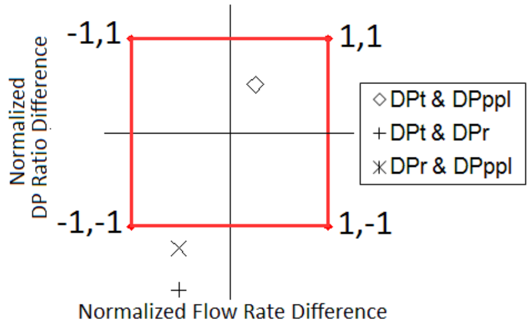

Fig 27. Light liquid load wet gas flow diagnostic results.

4.9. A saturated DP transmitter

A common problem with orifice meters is that the DP produced exceeds the transmitters range. In such a situation the transmitter is said to be "saturated". A saturated DP transmitter sends the upper range DP value to the flow computer instead of the actual higher DP value. The flow calculation will be supplied this erroneous low DP which it then combines with the keypad entered information to produce a flow rate prediction. Therefore, a saturated DP transmitter reading the traditional DP will produce a negative error.

There are no traditional internal meter diagnostics to indicate an operating error when the DP transmitter reading the traditional DP is saturated. Traditionally the meter operator must assume (i.e. hope) that the DP transmitter is not saturated between periodic checks.

In this air flow example a 4", 0.5 beta ratio orifice meter had a pressure of 29.9 bar(a), a temperature of 305K, a gas density of 37.0 kg/m^3 and a gas mass flow rate of 1.227 kg/s. With the data set being used here the DP was actually read correctly at 12,852Pa (i.e. 51.69"WC). However, if we consider the scenario where the DP transmitter had instead been spanned to 50"WC (i.e. 12,432Pa) then in this case the transmitter would have read 12,432Pa instead of the correct 12,852Pa. The resulting flow rate prediction would be 1.207 kg/s, i.e. a negative bias of 1.6%.

In the case of reading all three DP's directly, the first diagnostic warning comes from the fact that the fundamental rule relating the DP's appears not hold. That is, equation 1 does not hold:

$$\Delta P_t \neq \Delta P_r + \Delta P_{PPL} \quad \text{--- (1b).}$$

No physical malfunction can cause this result. In all the above mentioned physical problems applied to the meter body equation 1 holds true. However, in this case, when checking equation 1 the operator can tell the DP's being read are not trustworthy. The read DP's failing to follow equation 1 can only mean that one or more DP reading is not correct. That is, the simple check of equation 1 is a powerful diagnostic check of the health of the DP readings.

Figure 28 shows the saturated DP transmitter diagnostic result. This indicates that the orifice meter has a significant problem. As we already known from the DP reading check that the problem involves one or more DP reading error the diagnostic plot gives more information. We can see that the diagnostic point comprising of the recovered DP and the PPL is not affected by whatever issue is causing the warning. This is evidence to the meter operator that the problem is with the traditional DP reading, as that is the communal DP reading to the two diagnostic points outside the diagnostic box.

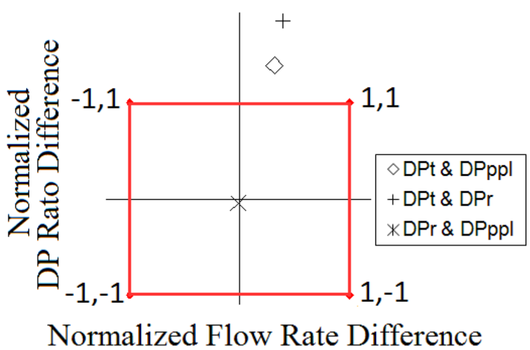

Fig 28. Saturated DP transmitter diagnostic results.

This is a random example showing the systems ability to see DP reading problems. The diagnostic method can likewise see many DP transmitter malfunctions, e.g. drifting DP transmitter, leaking 5-way manifold, incorrectly calibrated DP transmitter etc. This is the first orifice meter diagnostic system to show a flow rate prediction error when there is a DP transmitter malfunction.

4.10. Debris trapped at the orifice

A potential problem with orifice meters is debris lodged in the orifice. This creates a positive bias on the gas flow rate prediction. Debris trapped in the orifice changes the effective geometry of the orifice plate seen by the flow. This in turn changes the DP produced for any given flow condition from that which would have been produced if no debris was trapped in the orifice. The flow calculation will be supplied this DP produced by the flow through the partially blocked orifice. It then combines this DP and keypad entered information to produce a flow rate prediction. However, the keypad entered discharge coefficient is only valid for when the plate has no debris trapped in the orifice. Debris trapped in the orifice will produce a different discharge coefficient. Therefore, when the flow calculation receives the DP produced by the plate with trapped debris and uses the keypad entered discharge coefficient for a orifice with no trapped debris the flow rate prediction has an error.

If debris is trapped in the orifice there are no traditional internal meter diagnostics to indicate that the orifice meter is operating in error. Traditionally the meter operator must assume (i.e. hope) that there is no debris trapped in the orifice.


Fig 29. Rock trapped at an orifice plate.

Figure 29 shows a rock trapped in a 4", 0.4 beta ratio plate. The air flow test had flow conditions shown in Table 8.

Pressures	15 Bar
Traditional, DPt	11"WC <DPt< 400"WC
Expansion, DPr	8"WC <DPr< 32"WC
PPL, DPppl	99"WC<DPppl< 367"WC
Re Number	346e3 < Re < 2.15e6

Table 8. Trapped rock test data range.

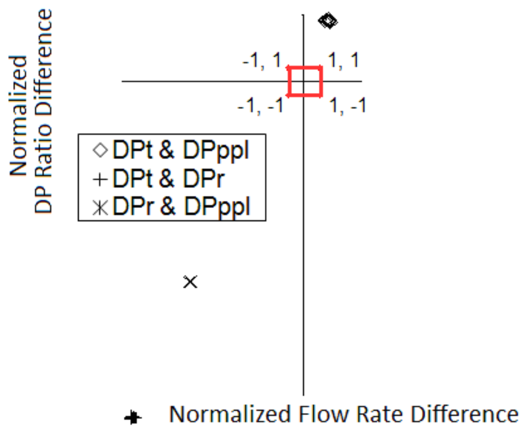

Fig 30. Rock trapped at orifice plate NDB plot.

Like all other physical meter problems (examples 4.1 to 4.8) the three read DP's are found to follow equation 1 indicating that the problem is not due to incorrect DP readings and is in fact an actual physical problem.

The gas flow prediction error was a positive bias of +117%. Figure 30 shows the associated diagnostic results indicating that the orifice meter has a significant problem. This is the first orifice meter diagnostic system to show a flow rate prediction error when there is debris trapped in the orifice.

Conclusions

Orifice meters have diagnostic capabilities. These patent protected orifice meter diagnostic methods are simple but **very** effective and of great practical use. The proposed method of plotting the diagnostic results on a graph brings the diagnostic results to the operator immediately in an easy to understand format.

These diagnostic methods for orifice meters have been developed by DP Diagnostics and the theory, laboratory testing and field trial results with major operators have been fully disclosed (e.g. see the BP technical paper describing these diagnostics being field tested at BP CATS in 2010 [4]). The technology is supplied by DP Diagnostics partners, Swinton Technology, via the software package called "Prognosis".

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3.ISO, "Measurement of Fluid Flow by Means of Pressure Differential Devices, Inserted in circular cross section conduits running full", no. 5167.

4. Skelton, M. "Diagnostics for Large High Volume Flow Orifice Plate Meters", North Sea Flow Measurement Workshop October 2010, St Andrews, Scotland, UK.