ORIFICE PLATE METER DIAGNOSTICS

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1. Introduction

Orifice plate meters are a popular for being relatively simple, reliable and inexpensive. Their principles of operation are 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

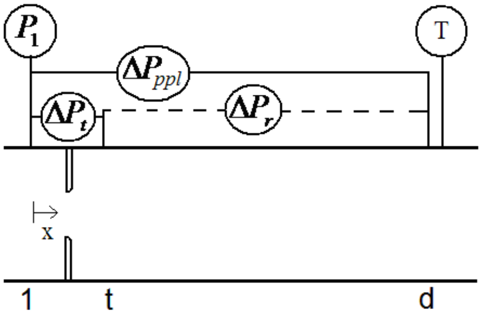


Fig 1. Orifice meter with instrumentation sketch.

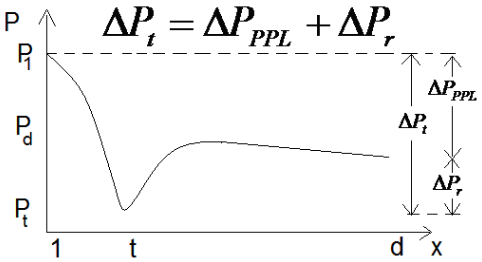


Fig 2. Simplified pressure fluctuation.

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").

The sum of the recovered DP and the PPL equals 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:

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

The traditional orifice meter flow rate equation is shown here as equation 2. Traditionally, this is the only DP meter flow rate calculation. However, with the additional downstream pressure tap three flow equations can be produced. That is, the recovered DP can be used to find the flow rate with an "expansion" flow equation (see equation 3) and the PPL can be used to find the flow rate with a "PPL" flow equation (see equation 4). Note $\dot{m}_t$, $\dot{m}_r$ & $\dot{m}_{PPL}$ represents the traditional, expansion and PPL mass flow rate equation predictions of the actual mass flow rate ($\dot{m}$) respectively. The symbol ρ represents the fluid density. Symbols E , A and A_t represent the velocity of approach (a constant for a set meter geometry), the inlet cross sectional area and the orifice (or "throat") cross sectional area through the meter respectively. Y is an expansion factor accounting for gas density fluctuation through the meter. (For liquids Y =1.)

The terms C_d, K_r & K_{PPL} represent the discharge coefficient, the expansion coefficient and the PPL coefficient respectively. These parameters are usually expressed as functions of the orifice meter geometry and the flows Reynolds number.

$$\mathrm{Re} = \frac{4\dot{m}}{\pi\mu D} \quad \text{--- (5)}$$

The Reynolds number is expressed as equation 5. Note that μ is the fluid viscosity and D is the inlet diameter. In this case, as the Reynolds number (Re) is flow rate dependent, these flow rate predictions must be individually obtained by iterative methods within the flow computer. A detailed derivation of these three flow rate equations is given by Steven [1].

Every orifice meter run is in effect three flow meters in series. As there are three flow rate equations predicting the same flow through the same meter body there is the potential to compare the flow rate predictions and hence have a diagnostic system. Naturally, all three flow rate equations have individual uncertainty ratings (say x%, y% & z% as shown in equations 2 through 4). Therefore, even if a DP meter is operating correctly, no two flow predictions would match *precisely*. However, a correctly operating meter will have no difference between any two flow rate predictions greater than the sum of the two uncertainties. The system therefore has three more uncertainties, i.e. the maximum allowable difference between any two flow rate equations, as shown in equation set 6a to 6c. This allows a self diagnosing system. If the percentage difference between any two flow rate equations is less than that equation pairs summed uncertainties, then no potential problem is found and the traditional flow rate prediction can be trusted. If however, the percentage difference between any two flow rate equations is greater than that equation pairs summed uncertainties then this indicates a metering problem and the flow rate predictions should not be trusted. The three flow rate percentage differences are calculated by equations 7a to 7c.

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. (The source of the three flow coefficients and their associated uncertainties will be explained in section 3.)

Traditional & PPL Meters allowable difference ($\phi\%$): $\phi\% = x\% + z\%$ -- (6a)

Traditional & Expansion Meters allowable difference ($\xi\%$): $\xi\% = x\% + y\%$ -- (6b)

Expansion & PPL Meters allowable difference ($\upsilon\%$): $\upsilon\% = y\% + z\%$ -- (6c)

Traditional to PPL Meter Comparison:

$$\psi\ \% = \left\{ \left(\dot{m}_{PPL} - \dot{m}_t \right) \Big/ \dot{m}_t \right\} * 100\% \quad \text{-- (7a)}$$

Traditional to Expansion Meter Comparison:

$$\lambda\ \% = \left\{ \left(\dot{m}_r - \dot{m}_t \right) \Big/ \dot{m}_t \right\} * 100\% \quad \text{-- (7b)}$$

PPL to Expansion Meter Comparison:

$$\chi\ \% = \left\{ \left(\dot{m}_r - \dot{m}_{PPL} \right) \Big/ \dot{m}_{PPL} \right\} * 100\% \quad \text{-- (7c)}$$

It is however 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 has a set relationship with the discharge coefficient and meter geometry when the flow is single phase homogenous flow. This is indicated by ISO 5167 [3]. We can rewrite Equation 1:

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

From equation 1a, if the PLR is a set 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 then also be set values. That is, all three DP ratios available from the three DP's read from a correctly operating orifice meter have a known relationship with the meter geometry and the discharge coefficient. Thus we have:

PPL to Traditional DP ratio (PLR):
$\left(\Delta P_{PPL} / \Delta P_t\right)_{set}$, uncertainty ± a%
Recovered to Traditional DP ratio (PRR):
$\left(\Delta P_r / \Delta P_t\right)_{set}$, uncertainty ± b%
Recovered to PPL DP ratio (RPR):
$\left(\Delta P_r / \Delta P_{PPL}\right)_{set}$, 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 percentage difference between this actual and correct operation PLR value as $\alpha\%$, the percentage difference between the actual and correct operation PRR value as $\gamma\%$, and the percentage difference between the actual and the correct operation RPR as η. These values are found by equations 8a to 8c.

$$\alpha\% = \{[PLR_{actual} - PLR_{set}] / PLR_{set}\} * 100\% \text{ -- (8a)}$$

$$\gamma\% = \{[PRR_{actual} - PRR_{set}] / PRR_{set}\} * 100\% \text{ -- (8b)}$$

$$\eta\% = \{[RPR_{actual} - RPR_{set}] / RPR_{set}\} * 100\% \text{ --(8c)}$$

An orifice meter with a downstream pressure tap can produce six meter parameters with nine associated uncertainties. These six parameters are the discharge coefficient, expansion flow coefficient, PPL coefficient, PLR, PRR and RPR. The nine uncertainties are the six parameter uncertainties (±x%, ±y%, ±z%, ±a%, ±b% & ±c%) and the three flow rate inter-comparison uncertainties ($\pm\phi\%$, $\pm\xi$, $\pm\upsilon\%$). ***These fifteen values define the DP meters correct operating mode.*** Any deviation from this mode is an indicator that there is an orifice meter malfunction, the meter is unserviceable and the traditional meter flow rate output is therefore not trustworthy. Table 1 shows the six possible situations that should signal an alarm. Note that each of the six diagnostic checks has normalized data, i.e. each meter diagnostic parameter output is divided by the allowable difference for that parameter.

For practical real time use, a graphical representation of the meters health continually updated on a control room screen could be simple and effective. However, any graphical representation of diagnostic results must be accessible and understandable at a glance by any meter operator. Therefore, it is proposed that three points are plotted on a normalized graph (as shown in Figure 3). This graphs abscissa is the normalized flow rate difference and the ordinate is the normalized DP ratio difference.

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_r & ΔP_{PPL}	$\|\chi\% / \upsilon\%\| \le 1$	$\|\chi\% / \nu\%\| > 1$
ΔP_t & ΔP_{PPL}	$\|\alpha\% / a\%\| \le 1$	$\|\alpha\% / a\%\| > 1$
ΔP_t & ΔP_r	$\|\gamma\% / b\%\| \le 1$	$\|\gamma\% / b\%\| > 1$
ΔP_r & ΔP_{PPL}	$\|\eta\% / c\%\| \le 1$	$\|\eta\% / c\%\| > 1$

Table 1. Potential diagnostic results.

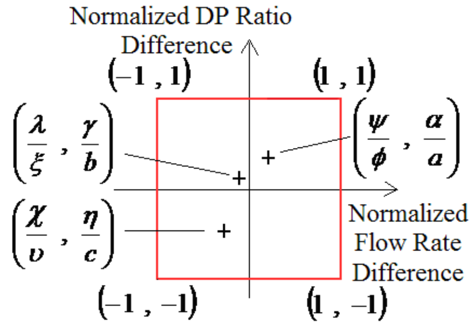


Fig 3. A normalized diagnostic calibration box with normalized diagnostic result.

These normalized values have no units. On this graph a normalized diagnostic box (or "NDB") can be superimposed with corner co-ordinates: (1, 1), (1, −1), (−1, −1) & (−1, 1). On such a graph three meter diagnostic points can be plotted, i.e. $(\psi/\phi, \alpha/a)$, $(\lambda/\xi, \gamma/b)$ & $(\chi/\upsilon, \eta/c)$. That is, the three DP's have been split into three DP pairs and for each DP pair the difference in the two flow rate predictions and, independently, the difference in the actual to set DP ratio are being compared to their maximum allowable differences. If all points are within or on the NDB 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. Correctly operating orifice plate meter data

Orifice meters tend to be installed according to the standards bodies recommendations. (This is usually the ASME MFC 3M, API 14.3 or ISO 5167 standards.) As a well made plate installed according to these standards recommendations has a repeatable performance the standards discharge coefficient statement is used without a meter calibration being required.

In this paper all orifice meter data, from correct and incorrect operation, are from plates installed according to the standards straight pipe inlet and outlet requirements, just as they are commonly installed in the field (except for deliberate tests for installation effects). Therefore, the orifice meter discharge coefficient can be taken from the standards (e.g. the Reader-Harris Gallagher, or "RHG" equation). This has an associated uncertainty value "x%". It should also be noted that ISO 5167 also offers a prediction for the PLR (see equation 9). From consideration of equation 1a we can then derive associated values for the PRR & RPR as shown is equations 10 & 11 respectively.

$$PLR = \frac{\sqrt{1-\left\{\beta^4\left(1-C_d^2\right)\right\}}-C_d\beta^2}{\sqrt{1-\left\{\beta^4\left(1-C_d^2\right)\right\}}+C_d\beta^2} \quad \text{-- (9)}$$

$$PRR = 1 - PLR \text{ -- (10)}, \quad RPR = \frac{PRR}{PLR} \text{ -- (11)}$$

Furthermore, it can be shown that from initial standards knowledge of the discharge coefficient and the PLR the expansion and PPL coefficients can be found as shown by equations 12 & 13.

$$K_r = \frac{YC_d}{\sqrt{1-PLR}} \text{ --(12)} \qquad K_{ppl} = \frac{E\beta^2 YC_d}{\sqrt{PLR}} \text{ --(13)}$$

Therefore, from the standards discharge coefficient and PLR predictions the expansion coefficient, PPL coefficient, PRR and RPR can be deduced. Unfortunately, no uncertainty value is given with the PLR prediction.

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 these orifice meters (i.e. downstream pressure port information inclusive) is very reproducible. The calibrated discharge coefficient was repeatedly shown to match the standards predictions to within the stated uncertainty and the ISO PLR prediction was also seen to be remarkably precise. Hence, from multiple tests at CEESI it was possible to assign reasonable uncertainty statements to the expansion coefficient, PPL coefficient, PLR, PRR and RPR parameters. It has subsequently been shown by further testing at CEESI, and in third party field trials, that these assigned uncertainty statements are reasonable. Hence, the three flow coefficients and the three DP ratios can be found from ISO statements and the uncertainties associated with these parameters (found from repeat orifice meter flow tests) can be assigned with some confidence to all orifice meters operating in the field.

Fig 4. Orifice fitting with natural gas flow.

Fig 5. Flange installed plate with air flow.

As part of these orifice meter tests three 4", 0.5 beta ratio flange tap orifice meter data sets were recorded at CEESI and analyzed by DP Diagnostics. The first is 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 maximum pressure recovery is guaranteed. 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.

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.

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 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 indicate 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 theoretically required due to data uncertainty.)

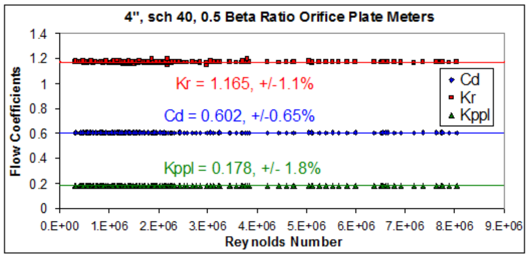


Fig 6. Combined 4", 0.5 beta ratio orifice plate meter flow coefficient results.

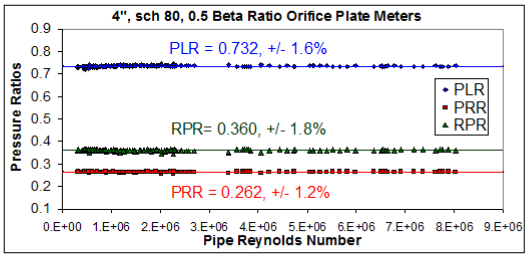
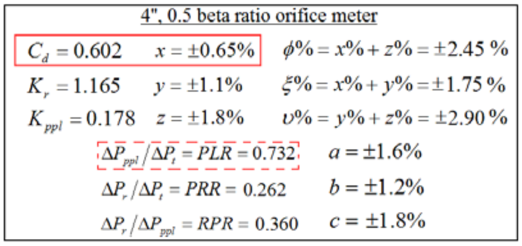


Fig 7. Combined 4", 0.5 beta ratio orifice plate meter DP ratio results.

For simplicity in this section of comparing this massed test data with the standards derived predictions we will use the data fit constant averaged values to compare against the standards predictions. ***Note that <u>in the field the individual point ISO predictions would be used</u> and as expected more than 95% of the discharge coefficient results here fitted the RHG equation to within this equations stated uncertainty of ±0.5%.***



4", 0.5 beta ratio orifice meter

$$\boxed{C_d = 0.602 \quad x = \pm 0.65\%} \quad \phi\% = x\% + z\% = \pm 2.45\ \%$$

$$K_r = 1.165 \quad y = \pm 1.1\% \quad \xi\% = x\% + y\% = \pm 1.75\ \%$$

$$K_{ppl} = 0.178 \quad z = \pm 1.8\% \quad \upsilon\% = y\% + z\% = \pm 2.90\ \%$$

$$\boxed{\Delta P_{ppl} / \Delta P_t = PLR = 0.732} \quad a = \pm 1.6\%$$

$$\Delta P_r / \Delta P_t = PRR = 0.262 \quad b = \pm 1.2\%$$

$$\Delta P_r / \Delta P_{ppl} = RPR = 0.360 \quad c = \pm 1.8\%$$

Fig 8. The results of a full DP meter calibration.

Figure 8 shows the full results of the combined analysis of the three separate orifice meter tests. The boxed information shows the traditional orifice plate meter parameter information used across industry, i.e. the discharge coefficient and its uncertainty to 95% confidence. The broken line box indicates a rare additional piece of information when a downstream pressure tap is included. Note even in this rare case, only the PLR is found. Traditionally none of these other parameters are considered and the downstream tap only exists to help predict the PPL across the component for overall hydraulic loss calculations on the piping system as a whole. However, from adding an extra pressure tap and DP transmitter, a standard orifice meter can be said to have six different parameters and nine associated uncertainties.

Each parameter tells the meter user something unique and of interest about the nature of the orifice meters response to the flow. *That is, an orifice plate meter with a downstream pressure port can produce several times more information than the same meter with no downstream pressure port.*

As previously stated in the field the meter would use the RHG discharge coefficient prediction and the ISO PLR prediction and then derive the expansion coefficient, PPL coefficient, PRR & RPR from this information. It is known the RHG equation has a low uncertainty of ½%. However, the ISO PLR prediction has no associated uncertainty assigned by ISO. It is therefore necessary to investigate the applicability of the ISO PLR prediction here.

	Data Fit Values	Data Fit % Spread	Prediction Values derived from ISO Cd & PLR	% Difference Between ISO & Data
Cd	0.602	±0.65%	N/A*	N/A*
Kr	1.165	±1.1%	1.167	+0.14%
Kppl	0.178	±1.8%	0.181	**+1.95%**
PLR	0.732	±1.6%	0.734	+0.23%
PRR	0.262	±1.2%	0.266	**+1.64%**
RPR	0.360	±1.8%	0.363	+0.82%

N/A* - Here we are using the data fit value, in the field the RHG equation will be more accurate at ±0.5%.

Table 5. Test data compared to ISO predictions.

Table 5 shows the combined test data average parameter values and the associated uncertainties versus the ISO predictions. First note that as the ISO discharge coefficient is Reynolds number dependent it is therefore individual flow point dependent. Hence it is not possible to directly compare the ISO individual discharge coefficient predictions with the test result values without going through every data point separately. However, as in excess of 95% of the combined orifice meter tests produced discharge coefficient values in agreement with RHG we can reasonably use the tests averaged constant discharge coefficient of 0.602 (with an uncertainty of 0.65%) as a very close representation of the RHG value that would be used in the field. We should note that the expansibility (Y) term used in equations 12 & 13 is a second order of magnitude term and can reasonably be approximated to unity *only for this particular purpose* of comparing test data diagnostic parameter results to ISO the predictions. We can now use these approximations to examine the *approximate* effectiveness of using the ISO PLR prediction with the RHG equation to predict the DP ratios and the expansion and PPL flow coefficients. This is also shown in Figure 5.

Even with these generalizing simplifying assumptions of a constant averaged discharge coefficient, an expansion factor of unity and accepting the ISO PLR prediction as correct the other derived “ISO predictions” are very similar to the experimental data results. The “ISO predicted” PPL flow coefficient and PRR are out with the data fitting uncertainty bands, but in both cases just marginally so. Furthermore, it should be remembered that in the field the discharge coefficient would be calculated per point with use of the RHG equation and the expansion factor would be applied. This will further reduce the uncertainty of these “ISO prediction” results. Therefore, an orifice meter user could calibrate his meter to find the full parameter set described here, or more practically for some small increase in uncertainty, the ISO based “predictions” could be used.

We now have enough orifice meter information to apply the normalized diagnostic box (NDB) when the meter is in service, and hence we have orifice meter diagnostics. When using these diagnostics it should be remembered that the primary output of the meter is the traditional flow rate prediction with its uncertainty rating. All other calculations are solely to check the validity of this output. False warnings regarding the meters health are highly undesirable. Therefore, as the uncertainty ratings of the diagnostic parameters are at 95% confidence, we need to increase these uncertainties somewhat to avoid periodic false warnings. Also note that when the third DP is not being directly measured, a small increase in diagnostic uncertainty values is prudent. (Note that these ***diagnostic*** uncertainty setting increases have nothing to do with the uncertainty rating of the primary output. The discharge coefficient can have one uncertainty rating for the output value and a separate larger uncertainty rating assigned for the diagnostic use of the parameter.) The uncertainties of the diagnostic parameters are set at the users discretion. Liberal uncertainty values are less likely to produce a false warning, but, this is obviously at the expense of diagnostic sensitivity. The larger the uncertainties, the less sensitive the meter is to small but real problems. The greatest possible diagnostic sensitivity and the greatest exposure to false warnings are both achieved with the smallest possible uncertainties, i.e. the calibrated values at 95% confidence.

4", 0.5 beta ratio orifice meter

$$C_d = 0.602 \quad x = \pm 1\% \quad \phi\% = x\% + z\% = \pm 4\%$$

$$K_r = 1.165 \quad y = \pm 2\% \quad \xi\% = x\% + y\% = \pm 3\%$$

$$K_{ppl} = 0.178 \quad z = \pm 3\% \quad \upsilon\% = y\% + z\% = \pm 5\%$$

$$\Delta P_{ppl} / \Delta P_t = PLR = 0.732 \quad a = \pm 2.6\,\%$$

$$\Delta P_r / \Delta P_t = PRR = 0.262 \quad b = \pm 2.2\%$$

$$\Delta P_r / \Delta P_{ppl} = RPR = 0.360 \quad c = \pm 4.0\%$$

Fig 9. Proposed practical orifice meter parameter uncertainty settings

For practical use in industry the ISO derived diagnostic parameter values should have uncertainties assigned that are above that found in the CEESI test results (see Figure 8). This minimizes the chance of false warnings. The values chosen by engineering judgment are shown in Figure 9. The judgment was made by taking into account the CEESI tests results and their comparison to the ISO parameter predictions. (Note that although Figure 9 also shows the CEESI data fits for the six diagnostic parameters with the suggested uncertainty ratings, in the field these uncertainty ratings will be assigned to the ISO predictions.)

Figure 10 shows a NDB with air flow test baseline (correct operation) data. ISO diagnostic parameter predictions were used with the associated uncertainties shown in Figure 9. It may appear that there is a mass of data here. However, note that as each flow point produces three DP pairs, every flow point tested has three diagnostic points on the graph. Therefore, the 17 test points produce 51 diagnostic points. *In actual application only three points representing three DP pairs would be superimposed on the graph at any one time making the diagnostics result very clear.* It is clear that no point for these correctly operating conditions is outside the NDB meaning the diagnostics are correctly declaring the meter to be serviceable. This result in itself could be seen as trivial as the uncertainties assigned to each diagnostic parameter was checked as reasonable against this very data. However, the non-trivial results are from orifice meters deliberately tested when malfunctioning for a variety of reasons.

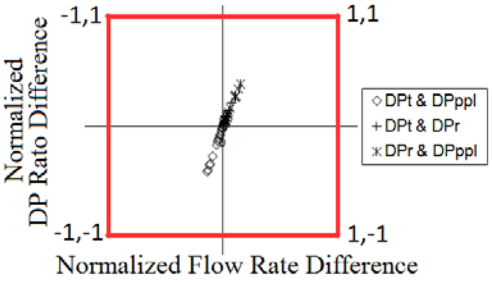


Fig 10. Correctly operating meter NDB results.

4. Incorrectly operating orifice plate meter data

There are many common orifice meter field problems. These scenarios are now discussed. ***All orifice meter diagnostic graphs shown in the examples use ISO parameter predictions with uncertainties shown in Figure 9.***

4.1. Incorrect Entry of Inlet Diameter

Modern orifice meter flow rate calculations are done by flow computers. The flow computer requires that the inlet diameter be keypad entered. If an error is made here a flow rate error will result. Traditionally there is no orifice meter self-diagnostic check to identify such an error.

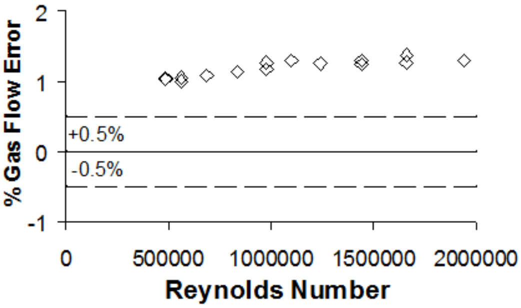


Fig 11. An inlet diameter flow prediction error.

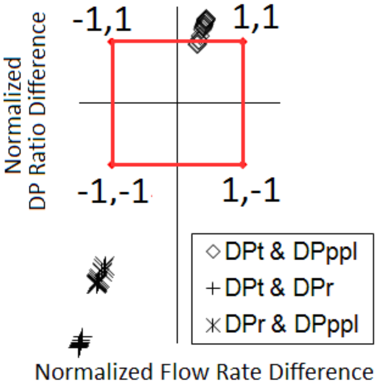


Fig 12. Inlet diameter error NDB result.

Figure 11 indicates the error induced if sample baseline data is 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”) is entered. The resulting error is a positive bias of approximately 1.5%. Figure 12 shows that the NDB plot that would be shown on the operators control room screen. (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.

4.2. Incorrect Entry of Orifice Diameter

The flow computer also requires that the orifice diameter be keypad entered. If an error is made here a flow rate error will result. Traditionally there is no orifice meter self-diagnostic check to identify such an error.

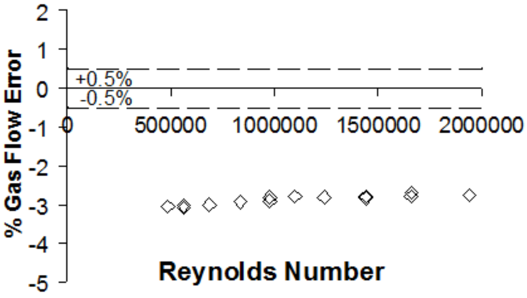


Fig 13. An orifice diameter flow prediction error.

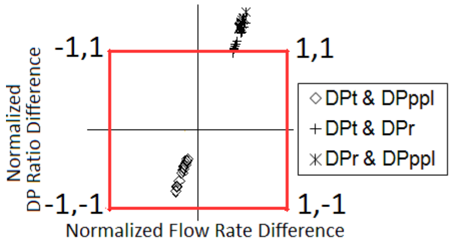


Fig 14. Orifice diameter error NDB result.

Figure 13 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. This sort of error can arise from incorrect measurement of the plate geometry or an incorrect diameter stated on the plates paper work. The resulting error is a negative bias of approximately 2.5%. Figure 14 shows that the NDB 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.

4.3. Reversed orifice plate installation

Orifice plates are often installed erroneously in the reverse (or “backwards”) direction to the flow. 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.

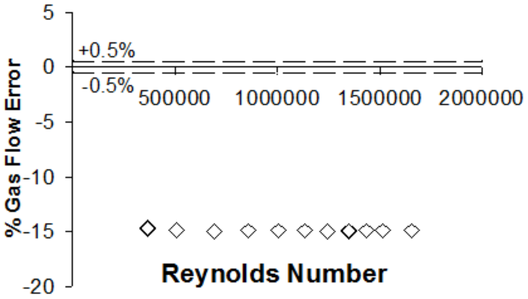


Fig 15. A backwards installed orifice plate error.

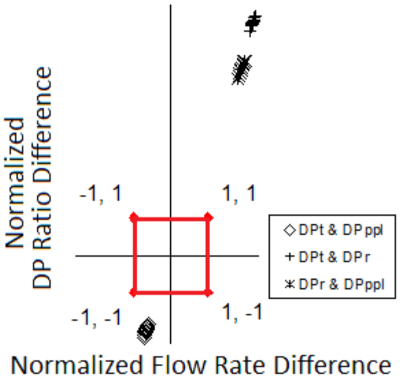


Fig 16. Backwards plate NDB result.

Figure 15 shows the repeatable flow rate prediction error (equation 2) with backwards installed plates. The error is a negative bias of approximately 15%.

There are no traditional internal meter diagnostics to indicate this problem. However the NDB data plot (Figure 16) very clearly indicates the problem. In this case as the problem is a precise geometry issue the precise pattern on the NDB indicates to the user the problem is most likely that the plate is installed backwards.

4.4. A moderately buckled (or “warped”) plate

Adverse flow conditions can damage orifice plates. A buckled plate can give significant flow measurement errors. Traditionally there is no diagnostic methodology to indicate this problem. A moderately buckled 4”, 0.5 beta ratio paddle plate was tested at CEESI. Figure 17 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.

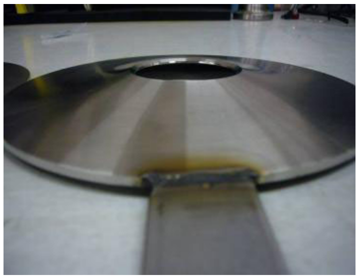


Fig 17. Moderately buckled orifice plate.

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.

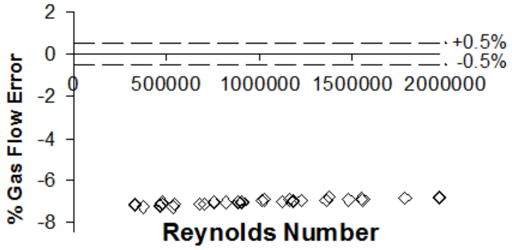


Fig 18. A buckled orifice plate meter error.

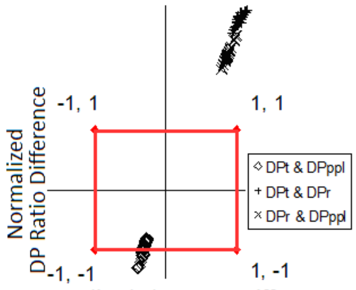


Fig 19. Buckled orifice plate meter NDB plot.

Figure 18 shows the flow rate prediction (equation 2) error due to the 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 19 shows the buckled plate data set plotted on a NDB. This indicates that the meter has a significant problem.

4.5. Worn leading orifice edge

Orifice plate sharp edges can be worn leading to flow measurement errors. Traditionally there is no diagnostic methodology to indicate this problem. 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 20 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.

Fig 20. Chamfered (0.02”) orifice edge.

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	352e3 < Re < 2.15e6

Table 8. Worn orifice plate edge test data range.

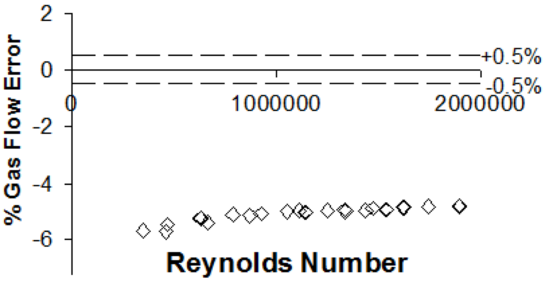


Fig 21. A worn edge orifice plate meter error.

Figure 21 shows the flow rate prediction (equation 2) error due to the orifice edge wear. The wear produces an approximate negative bias of 5%. Figure 22 shows the “worn” plate NDB data. This indicates that the orifice meter has a significant problem.

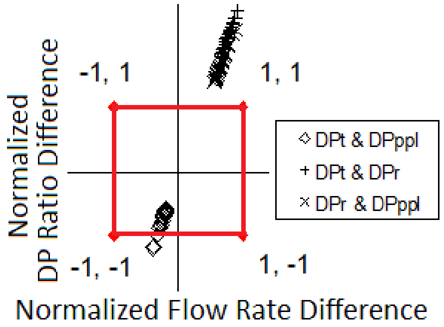


Fig 22. Worn edge orifice plate meter NDB plot.

4.6. Contaminated orifice plates

Contaminates can deposit on plates leading to orifice meter flow rate prediction errors. Traditionally there are no diagnostics to indicate this problem. 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 23 shows a 4”, 0.5 beta ratio paddle plate with this upstream surface contamination. Table 9 shows the test data ranges.

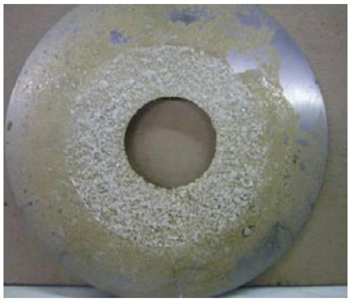


Fig 23. A heavily contaminated orifice plate.

Figure 24 shows the flow rate prediction (equation 2) error due to the plate contamination. The contamination produces an approximate negative bias of 3.5%. Figure 25 shows the contaminated plate NDB data. The recovered and traditional DP pair data points are all out side the NDB. This indicates that the orifice meter has a significant problem.

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	346e3 < Re < 2.15e6

Table 9. Contaminated plate test data range.

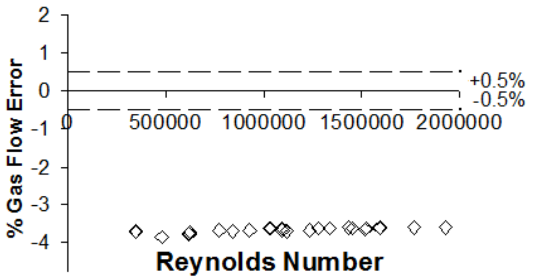


Fig 24. A heavily contaminated plate meter error.

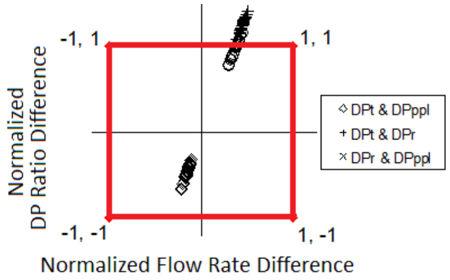


Fig 25. Heavily contaminated plate NDB plot.

4.7. Orifice plate meter installation effects

The standards state orifice meter installation requirements. If an orifice meter is installed too close to pipe components, or if loose debris is accidentally deposited upstream of the meter, the disturbances to the flow profile entering the meter can cause flow measurement errors. Traditionally there are no diagnostics to indicate this problem. Therefore, a half moon orifice plate (HMOP) was installed at 2D upstream of the meter to seriously disrupt the entry flow profile 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

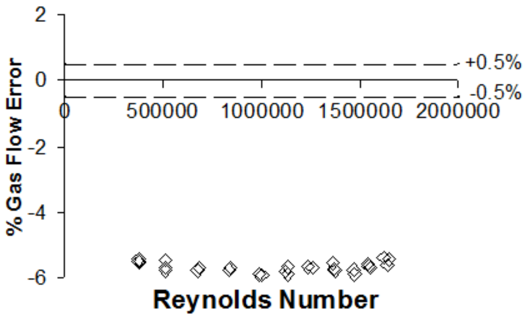


Fig 26. A velocity profile induced meter error.

Table 10 shows the test data ranges. Figure 26 shows the flow rate prediction (equation 2) error

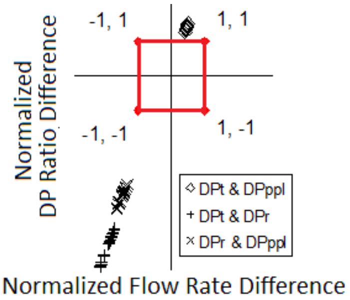


Fig 27. Disturbed velocity profile NDB plot.

due to the disturbed flow profile. The effect is an approximate negative bias of 5.5%. Figure 27 shows the disturbed velocity profile NDB data. This indicates that the orifice meter has a significant problem.

4.8. <u>Wet gas flows and orifice plate meters</u>

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 positive bias (or "over-reading") on an orifice meters gas flow rate prediction. Traditionally there are no diagnostics to indicate this problem.

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 found by 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. The liquid to gas mass ratio was therefore 0.12 (i.e. a GVF of 98.9%, a LVF of 1.1% and a Lockhart Martinelli parameter of 0.025). The orifice meter predicted the gas flow to be 3.43 kg/s, i.e. there was a positive gas flow rate bias (or an over-reading) of approximately 4%. Figure 28 shows this wet gas flow NDB data. This indicates that the orifice meter has a significant problem.

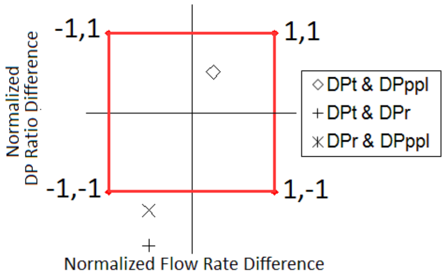


Fig 28. Light liquid load wet gas flow NDB plot.

4.9. <u>A saturated DP transmitter</u>

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" and it sends its maximum DP value to the flow computer. This is smaller than the actual DP. Hence the meter under predicts the flow rate. Traditionally there are no diagnostics to indicate this problem.

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%.

Figure 29 shows the saturated DP transmitter NDB data. This indicates that the orifice meter has a significant problem. We can see from Figure 29 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 may be with the traditional DP reading, as that is the common DP reading to the two diagnostic points outside the NDB.

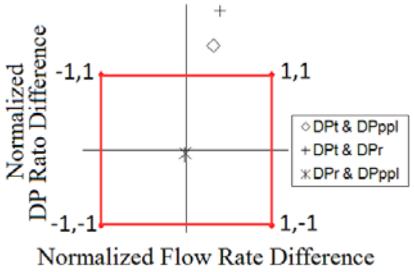


Fig 29. Saturated DP transmitter NDB plot.

In this example all three DP's were read directly. The other two DP transmitters gave the correct DP's and only the traditional DP transmitter had a fault. (Note that if more than one DP transmitter had a fault, for example two DP transmitters were saturated, the diagnostic warning would still have be seen – although a different pattern would have been produced outside the NDB.) This is a random example showing the systems ability to see DP reading problems. The system can see ***any*** significant DP reading problem, e.g. a blocked port, a drifting DP transmitter, poorly calibrated DP transmitter etc.

Due to transmitter uncertainty considerations, when only using two DP transmitters, it is best practice to read the largest (i.e. traditional) DP with the smallest of the other two DP’s. For orifice meters the smallest DP is the recovered DP. When only two DP transmitters are used, two of the three DP’s read are incorrect if one transmitter has a problem. The diagnostic warning still appears although the plot on the NDB is a different pattern. In this case of a saturated DP transmitter the use of only two DP transmitters would have also produced an error in the PPL value found. This would therefore shift both the traditional DP & PPL pair and recovered DP & PPL pair diagnostic points from the position in the plot shown in Figure 29. A correct diagnostic warning would still exist. However, as the recovered DP & PPL pair may also now indicate an error the indication that the problem may be with the traditional DP reading is lost. That is, by using less instrumentation some of the diagnostic capability is lost. Using two DP transmitters only still produces an extremely useful diagnostic system. However, if the application can justify the expense, it is technically better to use three DP transmitters as this gives the best diagnostic capability.

Finally, note that a diagnostic warning will be given if there is a significant error in ***any*** of the three DP readings. That is, if the traditional DP is correctly read, but one of the other DP’s is incorrect, then the meter will predict the correct gas flow rate yet signal a warning of incorrect operation. This is ***not*** a false warning. It is a real warning that something is wrong with the system as a whole. Some problems that trigger the diagnostic warning for a correct gas flow rate prediction can soon escalate to causing a flow rate prediction error. Therefore this should not be regarded as a false warning.

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. Traditionally there are no diagnostics to indicate this problem.

Figure 30 shows a rock trapped in a 4”, 0.4 beta ratio plate. The CEESI air flow test had flow conditions shown in Table 11. The gas flow prediction error was a positive bias of 117%.

Figure 31 shows the associated NDB data. This indicates that the
orifice meter has a significant problem.

Fig 30. Rock trapped at an orifice plate.

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 11. Trapped rock test data range.

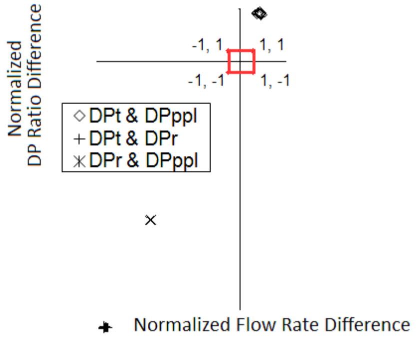


Fig 31. Rock trapped at orifice plate NDB plot.

Conclusions

Orifice meters have diagnostic capabilities. These patent pending 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 with a NDB brings the diagnostic results to the operator immediately in an easy to understand format.

References

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2.Steven, R. “Significantly Improved Capabilities of DP Meter Diagnostic Methodologies”, North Sea Flow Measurement Workshop October 2009, Tonsberg, Norway.

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