The Response of Orifice Meters & Their Diagnostic System to Wet Natural Gas Flow

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1. Introduction

Orifice plate meters are relatively simple, reliable and inexpensive. Their principles of operation are easily understood. However, traditionally there has been no orifice meter diagnostic capabilities. In 2008 & 2009 an orifice meter diagnostic methodology [1,2] was proposed. In this paper these orifice meters diagnostic principles are discussed and proven with experimental test results. The diagnostic results are presented in a simple graphical form for easy use in the field. A special case study of the orifice meters response to wet gas flow and the associated diagnostic output is also given.

2. A Technical Review of the Orifice Meter Diagnostic System

Fig. 1 shows an orifice plate meter with instrumentation sketch and the (simplified) pressure fluctuation (or "pressure field") through the meter body. This pressure field is **wholly** dependent on the combination of orifice meter geometry and the flow conditions. Therefore, the pressure field inherently contains a large amount of information regarding both the orifice meter geometry and the actual flow conditions. Since the initial conception of the orifice meter design, the very purpose of the primary element (i.e. the orifice plate) has been to create this pressure field so that a difference in pressure within the field can be read and related to the flow rate. Hence, the pressure field has **always** been an integral part of the orifice meter operating principle. However, traditionally, orifice meter users have not fully utilized this easily accessible and substantial pressure field information for flow metering or diagnostics purposes. Traditional orifice meters only compare the difference in pressure at two set points within this pressure field. Therefore, traditionally orifice meters are *needlessly* restricted in their capability compared to the substantial extra flow rate and diagnostic information that the pressure field as a whole has always offered. The orifice meter diagnostic methods discussed here open up the potential of more closely monitoring the pressure field as a whole, thereby significantly increasing the capabilities of orifice meters on which the diagnostics are applied.

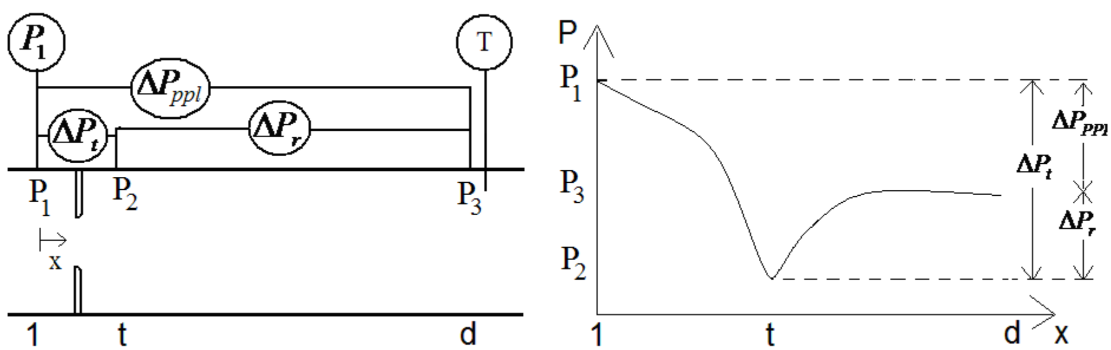

Fig 1. Orifice meter with instrumentation sketch and pressure fluctuation graph.

Traditional orifice meters read the inlet pressure (P_1), the downstream temperature (T) and the differential pressure (ΔP_t) between the inlet pressure tap (P_1) and a pressure tap positioned in the vicinity of the point of low pressure (P_2), created by the primary element. That is, traditionally DP meter technology only takes a single DP measurement from the pressure field. However, note that the DP meter run in Figure 1 has a third pressure tap (P_3) further downstream of the primary element. This allows the measurement of two extra DP's. That is, it allows extra pressure field information to be read. The two extra DP's are the differential pressure between the downstream (P_3) and the low (P_2) pressure taps (or "recovered" DP, ΔP_r) and the differential pressure between the inlet (P_1) and the downstream (P_3) 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 **must** equal the traditional differential pressure (equation 1).

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

Traditional Flow Equation: $\dot{m}_t = EA_t Y C_d \sqrt{2\rho\Delta P_t}$, uncertainty ± x% --- (2)

Expansion Flow Equation: $\dot{m}_r = EA_t K_r \sqrt{2\rho\Delta P_r}$, uncertainty ± y% --- (3)

PPL Flow Equation: $\dot{m}_{ppl} = AK_{PPL} \sqrt{2\rho\Delta P_{PPL}}$, uncertainty ±z% --- (4)

The traditional orifice meter flow rate equation is shown here as equation 2. Traditionally, this is the only orifice meter flow rate calculation. However, with the additional downstream pressure tap three flow equations can be produced. The recovered DP can be used to find the flow rate with an “expansion” flow equation (see equation 3). The PPL can be used to find the flow rate with a “PPL” flow equation (see equation 4). Note $\dot{m}_t$, $\dot{m}_r$ and $\dot{m}_{PPL}$ 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 inlet fluid density. Symbols E , A and A_t represent the geometric constants of the velocity of approach, the inlet cross sectional area and the minimum (or “throat”) cross sectional area through the meter respectively. The parameter Y is an expansion factor accounting for gas density fluctuation through the meter. (For liquids Y =1.) The terms C_d, K_r and K_{PPL} represent the discharge coefficient, the expansion coefficient and the PPL coefficient respectively.

Every orifice meter body is in effect three flow meters. 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 an orifice meter is operating correctly, no two flow predictions would match *precisely*. However, a correctly operating orifice meter should have no difference between any two flow rate predictions greater than the root mean square value of the two flow prediction uncertainties. Therefore, the maximum allowable difference between any two flow rate equations, i.e. $\phi\%$, $\xi\%$ & $\upsilon\%$ is shown in equation set 5a to 5c. If the percentage difference between any two flow rate predictions is less than the root mean square of those two flow rate prediction uncertainties, then no potential problem is found. If however, the percentage difference between any two flow rate predictions is greater than the root mean square of those two flow rate prediction 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 6a to 6c.

Traditional & PPL Meters % allowable difference $\phi\% = \sqrt{(x\%)^2 + (z\%)^2}$ --- (5a)

Traditional & Expansion Meters % allowable difference: $\nu\% = \sqrt{(y\%)^2 + (z\%)^2}$ --- (5b)

Expansion & PPL Meters % allowable difference: $\xi\% = \sqrt{(x\%)^2 + (y\%)^2}$ --- (5c)

This diagnostic methodology uses the three individual DP’s to independently predict the flow rate and then compares these results. With three flow rate predictions, there are three flow rate predictions pairs and therefore three flow rate diagnostic checks. In effect, the individual DP’s are therefore being directly compared. However, it is possible to take a different diagnostic approach.

Traditional to PPL Meter Comparison : $\psi\% = \left\{ \left(\dot{m}_{PPL} - \dot{m}_t \right) \Big/ \dot{m}_t \right\} * 100\%$ --- (6a)

Traditional to Expansion Meter Comparison: $\lambda\% = \left\{ \left(\dot{m}_r - \dot{m}_t \right) \Big/ \dot{m}_t \right\} * 100\%$ --- (6b)

PPL to Expansion Meter Comparison: $\chi\% = \left\{ \left(\dot{m}_r - \dot{m}_{PPL} \right) \Big/ \dot{m}_{PPL} \right\} * 100\%$ --- (6c)

The **P**ressure **L**oss **R**atio (or "PLR") is the ratio of the PPL to the traditional DP. Like the orifice meter flow coefficients the PLR is a meter characteristic for the orifice meter operating with single phase homogenous flow. It can be expressed as a constant value or related to the Reynolds number. We can rewrite Equation 1:

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

From equation 1a, if PLR is a set value (for any given Reynolds number) 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 DP ratios available from the three DP pairs are constant values for any given orifice meter geometry and Reynolds number. Thus we also have:

PPL to Traditional DP ratio (PLR): $(\Delta P_{PPL} \ / \ \Delta P_t)_{calibration}$, uncertainty ± a%

Recovered to Traditional DP ratio (PRR): $(\Delta P_r \ / \ \Delta P_t)_{calibration}$, uncertainty ± b%

Recovered to PPL DP ratio (RPR): $(\Delta P_r \ / \ \Delta P_{PPL})_{calibration}$, uncertainty ± c%

Here then is another method of using the three DPs to check an orifice meters health. Actual DP ratios found in service can be compared to the fixed known correct values. Let us denote the percentage difference between the found PLR and the known correct value as $\alpha\%$, the difference between the found PRR and the known correct value as $\gamma\%$, and the difference between the found RPR and the known correct value as $\eta\%$. These values are found by equations 7a to 7c.

$$\alpha\% = \{[PLR_{actual} - PLR_{calibration}] / PLR_{calibration}\} * 100\% \quad \text{--- (7a)}$$

$$\gamma\% = \{[PRR_{actual} - PRR_{calibration}] / PRR_{calibration}\} * 100\% \quad \text{--- (7b)}$$

$$\eta\% = \{[RPR_{actual} - RPR_{calibration}] / RPR_{calibration}\} * 100\% \quad \text{--- (7c)}$$

If the percentage difference between the in-service and the known correct DP ratio is less than the stated uncertainty of that known DP ratio value, then no potential problem is found. If the percentage difference between the in-service and the known correct DP ratio is greater than the stated uncertainty of that known DP ratio value, then a potential problem is found and the flow rate predictions should not be trusted. With three DP ratios, there are three DP ratio diagnostic checks.

These three flow coefficients and three DP ratios can be derived from ISO 5167 – Part 2 [3]. This standard gives an expression for the discharge coefficient (C_d) and the PLR. From these two pieces of information the other two flow coefficients and the other two DP ratios can be directly derived. The derivation of these parameters is beyond the scope of this paper. However, the interested reader can find the full derivation in Steven [1,2].

Equation 1 holds true for all orifice meters. It is a consequence of the first law of thermodynamics and as such it cannot be violated, even if an orifice meter has malfunctioned. Therefore, if all three DP's are read they can be checked against equation 1. As this equation must hold true, any result that suggests that it does not hold true is a statement by the diagnostic system that there is an erroneous DP reading coming from the instrumentation (regardless of whether the meter body is serviceable or not). An orifice meter reading all three DP's can infer the actual traditional DP (ΔP_t) by summing the read recovery DP (ΔP_r) and permanent pressure loss (ΔP_{PPL}). This gives an inferred traditional DP ($\Delta P_{t,\inf}$) that can be compared to the directly read traditional DP ($\Delta P_{t,read}$). Whereas theoretically these traditional DP values are the same, due to the uncertainties of the three DP transmitters, even for correctly read DP's, they can be slightly different. The percentage difference ($\delta\%$) can be calculated as seen in equation 8.

$$\delta\% = \{(\Delta P_{t,\inf} - \Delta P_{t,read}) / \Delta P_{t,read}\} * 100\% \quad \text{--- (8)}$$

The uncertainty of each DP read will be known from the individual DP transmitter specifications. Therefore, it is possible to assign a maximum allowable percentage difference ($\theta\%$) between the directly read and inferred traditional DP values. However, it has been found in practice that setting $\theta\% = 1\%$ is a reasonable practical value that covers a wide range of DP's measured. Therefore, if the percentage difference between the directly read and inferred traditional DP values ($\delta\%$) is less than the allowable percentage difference ($\theta\%$), then no potential problem is found. However, if the percentage difference between the directly read and inferred traditional DP values ($\delta\%$) is greater than the allowable percentage difference ($\theta\%$), then a problem with the DP measurements is confirmed and the flow rate predictions cannot be trusted.

Table 1 shows the seven possible situations that would signal a meter system malfunction. Each of the seven diagnostic checks has ***normalized data***, i.e. each diagnostic parameter percentage difference is divided by the allowable percentage difference for that parameter to produce the same warning criteria of out with: -1 ≤ diagnostic result ≤ 1. For convenience we use the following naming convention for the normalized data:

Normalized flow rate inter-comparisons: $x_1 = \psi\%/\phi\%$, $x_2 = \lambda\%/\xi\%$, $x_3 = \chi\%/\upsilon\%$

Normalized DP ratio comparisons: $y_1 = \alpha\%/a\%$, $y_2 = \gamma\%/b\%$, $y_3 = \eta\%/c\%$

Normalized DP sum comparison: $x_4 = \delta\%/\theta\%$

DP Pair	No Warning	WARNING	No Warning	WARNING
ΔP_t & ΔP_{ppl}	$-1 \le x_1 \le 1$	$-1 < x_1$ or $x_1 > 1$	$1 \le y_1 \le 1$	$-1 < y_1$ or $y_1 > 1$
ΔP_t & ΔP_r	$-1 \le x_2 \le 1$	$-1 < x_2$ or $x_2 > 1$	$1 \le y_2 \le 1$	$-1 < y_2$ or $y_2 > 1$
ΔP_r & ΔP_{ppl}	$-1 \le x_3 \le 1$	$-1 < x_3$ or $x_3 > 1$	$1 \le y_3 \le 1$	$-1 < y_3$ or $y_3 > 1$
$\Delta P_{t,read}$ & $\Delta P_{t,\inf}$	$-1 \le x_4 \le 1$	$-1 < x_4$ or $x_4 > 1$	N/A	N/A

Table 1. The DP meter possible diagnostic results.

For practical real time (or historical auditing) use, a graphical representation of the diagnostics continually updated on a control room screen (while being archived) can be simple and effective. Any such graphical representation of diagnostic results should be immediately accessible and understandable to the average operator. Therefore, four points are plotted on a normalized graph (as shown in Fig 2). This graph's abscissa and ordinate (i.e. x & y axis) are number lines only, i.e. the axis have no units. On this graph a **n**ormalized **d**iagnostic **b**ox (or "NDB") can be superimposed with corner co-ordinates: (1,1), (1,-1), (-1,-1) & (-1,1). On such a graph four meter diagnostic points can be plotted, i.e. (x_1,y_1), (x_2,y_2), (x_3,y_3) & (x_4,0). Therefore, first, the three

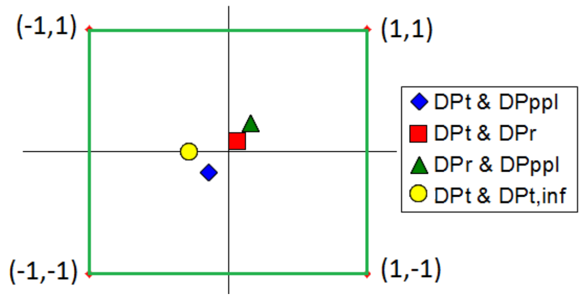

Fig 2. Normalized diagnostic box (NDB) with diagnostic results

directly read DP's have been split into three DP pairs and for each pair both the difference in the flow rate predictions and the difference in the actual to set known DP ratio are being compared to the maximum allowable differences. Secondly, the difference between the directly read and inferred traditional DP and is being compared to the maximum allowable difference. The abscissa is being used as a number line when the value $\delta\%/\theta\%$ (x_4) is being plotted (and the ordinate value is therefore zero by default). If the resulting diagnostic value falls within $-1 \le x_4 \le +1$ then the point $(x_4, 0)$ falls inside the NDB and no DP reading problem is noted. If the resulting diagnostic value falls out with $-1 \le x_4 \le +1$ then the point $(x_4, 0)$ falls outside the NDB and a DP reading problem is noted. If all points are within 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 points falls outside the NDB the meter operator has an indication that the meter is ***not*** operating correctly and that the meters traditional (or any) flow rate prediction cannot be trusted.

If the DP's are read correctly the diagnostics show $-1 \le x_4 \le +1$ regardless of whether there is any meter malfunction. A physical meter malfunction, where the DP's are still being correctly read, will be indicated by $-1 \le x_4 \le +1$ with one or more of the **other** diagnostic points outside the box. Such a plot indicates the problem is with the meter body and <u>not</u> the DP readings. However, if the DP readings are erroneous then the diagnostics will show that $-1 \le x_4 \le +1$ does not hold (i.e. this diagnostic point is outside the NDB) and therefore the DP readings **must** be erroneous. Therefore, such a plot as Figure 2 allows the meter operator to not only see a problem but be able to distinguish the problem between a secondary DP instrumentation problem and a primary meter body based physical problem. 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 2 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 [1,2] 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 (at various test facilities and field locations) 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 uncertainty statements to these six parameters.

Three 4", 0.5 beta ratio flange tap orifice meter data sets were recorded at CEESI. The first was a natural gas flow test on an orifice fitting installed plate (see Figure 3). In these tests only the traditional DP and PPL were read. The downstream pressure port is six diameters downstream of the back face of the plate as this is where ISO suggest DP recovery is complete. The recovered

Fig 3. Orifice fitting with natural gas flow.

Fig 4. Flange installed plate with air flow.

DP was derived by equation 1. The other two data sets are from separate air flow, flange installed paddle plate orifice meter tests carried out at CEESI (see Figure 4). The first tests used Daniel plates. The second tests use Yokogawa plates. These air tests both directly read all three DP's. The downstream pressure port was at six diameters downstream of the back face of the plate.

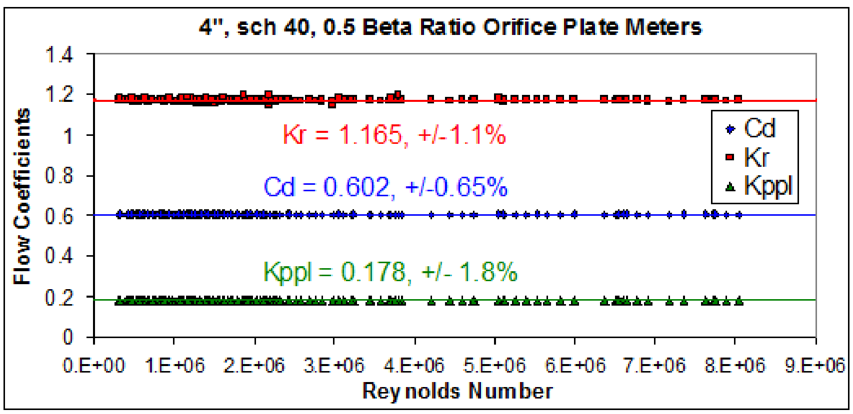

Fig 5. Combined 4", 0.5 beta ratio orifice plate meter flow coefficient results.

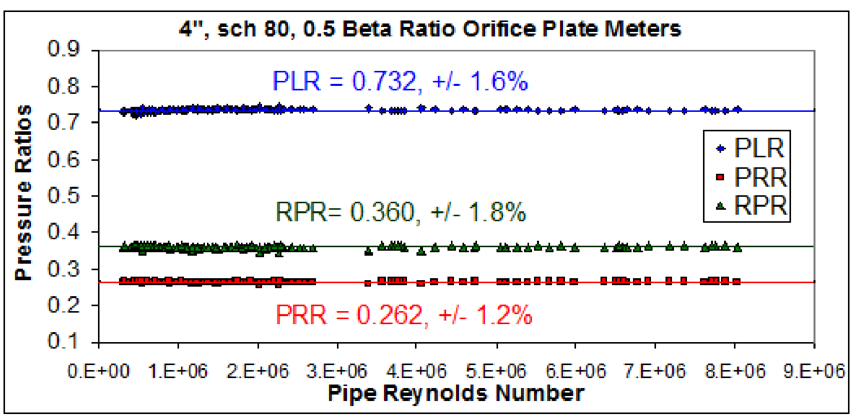

Fig 6. Combined 4", 0.5 beta ratio orifice plate meter DP ratio results.

Flow Coefficient	Uncertainty	DP Ratio	Uncertainty
Cd	1.0%	PLR	3%
Kr	2.5%	PRR	2.5%
Kppl	2.5%	RPR	4%

Table 2. Assigned Uncertainty Values

Figure 5 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 6 shows the average constant value PLR, PRR & RPR from all three data sets analyzed together and the associated uncertainty values of the fit. All six parameters exist at relatively low uncertainty and 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 2 shows the uncertainty values for each of the diagnostic parameters.

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 <u>these diagnostics do not interfere in any way with the normal operation of the orifice meter</u>. 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 discharge coefficient 1.0% uncertainty is solely for use in the diagnostics system, where this increase is to reduce the sensitivity of the diagnostic system to avoid false warnings.

Figure 4 shows a sample baseline diagnostic result. This is the actual diagnostic plot from a correctly operating 4”, 0.5 beta ratio orifice meter tested with air at 433 psia and 3.2 lb/s. The points are all inside the box thereby indicating correctly that the meter is serviceable. This result in itself could be seen as trivial as this orifice meter was carefully set up by in the 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.

A malfunctioning orifice meter produces diagnostic co-ordinate patterns on the NDB plot that can be caused by some malfunctions and cannot be caused by other malfunctions. Hence, a pattern found in service does not just alert the operator to the meter malfunction but gives a short list of malfunctions that could cause such a pattern while excluding malfunctions that create different diagnostic patterns. This of course is of significant benefit to the maintenance crews.

4. <u>Orifice Meter Malfunctions and the Diagnostic System’s Response</u>

4a. <u>Incorrect KeyPad Entry Values of Meter Geometry</u>

A 4” sch 40 orifice meter has a inlet diameter of 4.026”and a orifice diameter of 2.000”. The beta ratio is 0.4967. When this geometry is correctly supplied to the flow computer and the metering system has no malfunctions the diagnostic system will show all points inside the NDB. However, a common problem is incorrect keypad entries, i.e. human error. In this example an incorrect inlet diameter of sch 80 diameter of 3.826” was entered. The resulting flow rate prediction error is +1.3%. Traditionally there are no diagnostics that would register this problem.

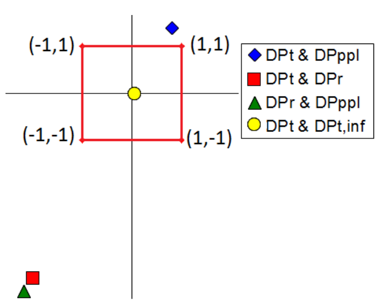

Fig 7. Incorrect Inlet Diameter Geometry

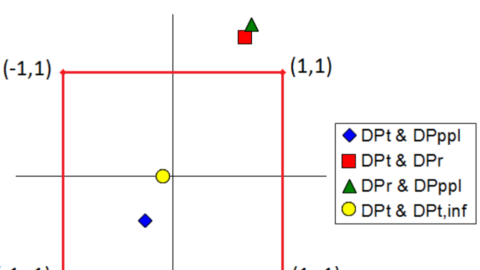

Fig 8. Incorrect Orifice Diameter Geometry

Fig 7 shows the corresponding diagnostic result for data recorded with air at 433 psia and 5.44 lb/s. The DP check (yellow circle) is inside the NDB indicating that the DP's are correct. The other three points indicate a malfunction. The problem is therefore something to do with the meter body or flow conditions. Too low an inlet diameter is included in the short list of problems associated with this diagnostic pattern.

Figure 8 shows the response of the diagnostic system if, for the same flow conditions as the above example, the flow computer has the correct inlet diameter but an incorrect orifice diameter. Here, an orifice diameter of 1.972" has been entered instead of the actual 2.000". The corresponding flow rate prediction error is -2.6%. Traditionally there are no diagnostics internal to the orifice meter system that would register this problem. The DP check (yellow circle) is inside the NDB indicating that the DP's are correct. Two of the three other points indicate a malfunction. The problem is therefore something to do with the meter body or flow conditions. Too low an orifice diameter is included in the short list of problems associated with this diagnostic pattern.

4b. <u>Reversed / Backwards Plate Installation</u>

A common problem is the installation of the orifice plate meter "backwards", or "reversed", meaning the bevel is upstream. This induces a negative bias. The scale of the bias is beta ratio dependent. Traditionally there are no diagnostics that would register this problem. A 4", sch 40, 0.5 beta ratio orifice meter was run with a reversed plate. The air pressure in this example was 217 psia and the gas flow rate was 4.4 lb/s. The induced bias was -15%.

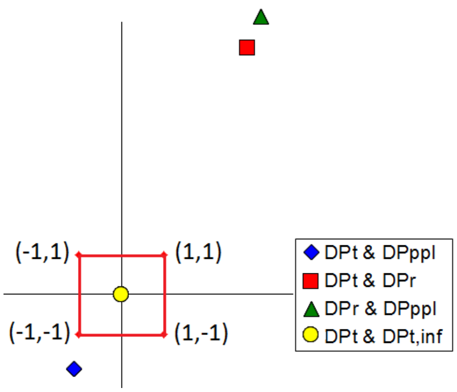

Fig 9. Reversed Plate Diagnostic Result

Fig 9 shows the corresponding diagnostic result. The DP check (yellow circle) indicates that the DP's are correct. The other three points indicate a malfunction. The problem is therefore something to do with the meter body or flow conditions. For any given orifice plate geometry reversing the plate produces a reproducible change in geometry and meter performance. A set beta ratio reversed plate therefore reproduces set diagnostic co-ordinates indicating a reversed orifice plate.

4c. <u>Worn Orifice Edge Examples</u>

An orifice plate's sharp edge can become worn inducing a negative bias on the flow rate prediction. Contrary to common belief, it takes substantial damage to the sharp edge to cause a significant flow rate prediction error. As such a 4", sch 40, 0.5 beta ratio plate had the sharp edge chamfered to 0.02" (see Fig 10). The resulting bias when the meter was tested at an air pressure of 435 psia and a flow rate of 6.3 lb/s was -4.8%. The diagnostic result is shown in Fig 11.

Fig 10. Chamfered (0.02") orifice edge.

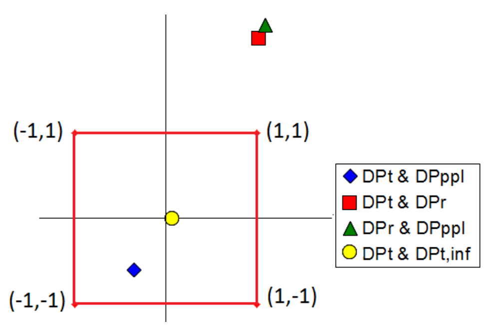

Fig 11. Worn Orifice Edge.

The DP check indicates that the DP's are correct. Two of the three other points indicate a malfunction. The problem is therefore something to do with the meter body or flow conditions. A worn orifice plate edge is included in the short list of problems associated with this diagnostic pattern. Traditionally there are no diagnostics internal to the orifice meter system that would register this problem.

Note that the reversed plate and worn edge are similar examples showing the diagnostic system's reaction to a beveled / worn edge plate. In service, when erosion becomes worse the diagnostic pattern will trend with the changing performance of the meter. This trending capability is also useful in several other scenarios such as contamination problems and as will be described in detail in section 6, wet gas flow.

4d. Buckled Plate Example

An orifice plate can buckled by temporary extreme adverse flow conditions. Traditionally there are no diagnostics that would register this problem. A buckled plate induces a negative bias on the flow rate prediction. A moderately buckled 4", 0.5 beta ratio paddle plate (see Fig 13) was tested at an air pressure 218 psia and a flow rate of 2.5 lb/s. The induced negative flow rate prediction bias was -7%. The diagnostic result is shown in Fig 12.

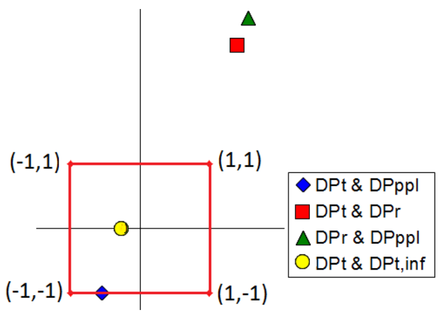

Fig 12. Buckled Orifice Plate Diagnostic Result.

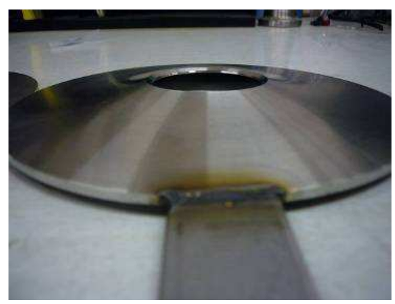

Fig 13. Buckled Orifice Plate

The DP check indicates that the DP's are correct. Two of the three other points indicate a malfunction. The problem is therefore something to do with the meter body or flow conditions. A buckled plate is included in the short list of problems associated with this diagnostic pattern.

4e. Contaminated Orifice Plate Example

Contaminates in the production flow can contaminate the plate and the meter run. Contamination induces a negative bias on the flow rate prediction. Traditionally there are no diagnostics that would register this problem. A contaminated 4", 0.5 beta ratio paddle plate (see Fig 14) was tested at an air pressure of 435 psia and a flow rate of 4.26 lb/s. The induced negative flow rate prediction bias was -3.5%. The diagnostic result is shown in Fig 15. The DP check shows that the DP's are correct. Two of the three other points indicate a malfunction, hence the problem is something to do with the meter body or flow conditions. Contamination is included in the short list of problems associated with this diagnostic pattern.

Fig 14. Contaminated Orifice Plate.

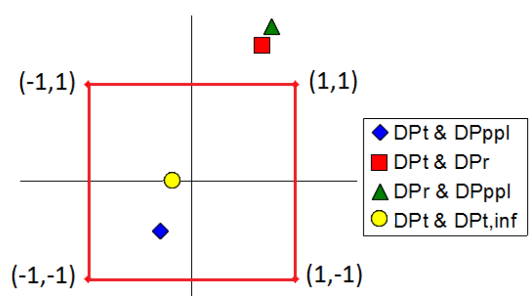

Fig 15. Worn Orifice Edge Diagnostic Result.

4f. Debris Trapped at Orifice

Debris from wells can become trapped t the orifice. Trapped debris induces a positive bias on the flow rate prediction. Traditionally there are no diagnostics that would register this problem. A 4", 0.5 beta ratio orifice plate with a trapped rock (see Fig 16) was tested at an air pressure of 215 psia and a flow rate of 1.2 lb/s. The induced negative flow rate prediction bias was +117%. The diagnostic result is shown in Fig 17. The DP check shows that the DP's are correct. The three other points indicate a malfunction, hence the problem is something to do with the meter body or flow conditions. A partially plugged orifice is included in the short list of problems associated with this diagnostic pattern.

Fig 16. Rock Trapped at an Orifice Plate.

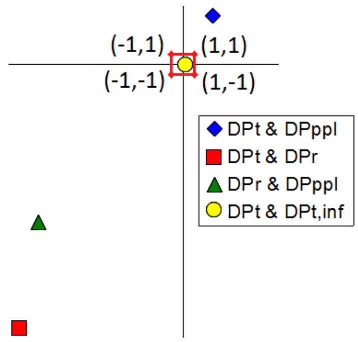

Fig 17. Trapped Rock Diagnostic Result.

4g. Disturbed Inlet Flow

The orifice meter requires a fully developed flow profile at the meter inlet. If the inlet flow is disturbed, e.g. by upstream pipe work components being too close or by a partially blocked flow conditioner, then a flow rate prediction error may be induced. The direction of this error is case dependent. Traditionally there are no diagnostics that would register this problem.

Contrary to common belief, it takes a substantial flow disturbance to cause a significant flow rate prediction error. As such a 'half-moon' orifice plate (HMOP) was positioned at 2D upstream of the 4", 0.5 beta ratio orifice plate meter to create a significant flow disturbance at the meter inlet (see Fig 19). For an air pressure of 217 psia and a flow rate of 3.3 lb/s the induced negative flow rate prediction bias was -5.5%. The diagnostic result is shown in Fig 18. The DP check shows that the DP's are correct. The three other points indicate a malfunction, hence the problem is something to do with the meter body or flow conditions. Disturbed flow is included in the short list of problems associated with this diagnostic pattern.

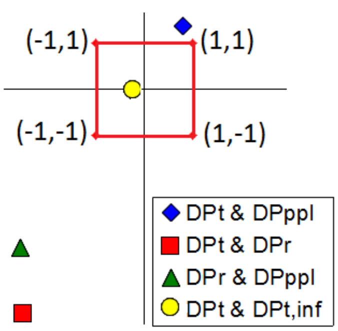

Fig 18. Disturbed Inlet Flow Diagnostic Result.

Fig 19. Half-Moon Plate Disturbance.

4h. DP Transmitter Malfunctions

The preceding examples are all for the case of the DP transmitters operating correctly. However, many meter errors are due to DP readings being erroneous. In this example consider the case where a 4", sch 40, 0.5 beta ratio orifice meter has a DP transmitter malfunction. For an air pressure of 434 psia and a flow rate of 2.7 lb/s the true traditional DP created was correctly read as 51.7"WC (i.e. 12.85 kPa). However, by way of an example, if the upper range limit of the DP transmitter had been say, 50.0"WC (i.e. 12.43 kPa) then the DP transmitter would have been 'saturated' and the traditional DP would have been erroneously read as 50.0"WC instead of 51.7"WC. The corresponding negative flow rate prediction bias is approximately -1.7%.

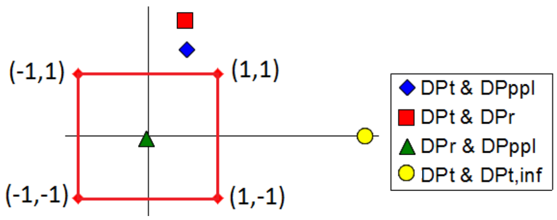

Fig 20. Saturated DP Transmitter (Erroneous DP) Diagnostic Result.

Fig 20 shows the corresponding diagnostic result. The DP check (yellow circle) is outside the NDB stating that at least one of the DP readings is erroneous. Two of the other three diagnostic points are also outside the NDB. As we know the cause of the problem is DP reading error/s the pattern contains further information. It is evident that the diagnostics associated with the recovered and PPL DP pair are unaffected by the problem. Therefore, it is evident these two DP readings are correct. These diagnostic methods do not utilize the traditional DP measurement. The other two diagnostic points, i.e. those associated with the traditional & recovered DP pair and the traditional & PPL DP pair, are both outside the NDB. The communal DP to both these points is the traditional DP. Hence, it is deduced that the DP reading with the malfunction is the traditional DP while the other two DP readings are correct.

Once it is ascertained that the traditional DP is being read incorrectly, but the other two DP's are read correctly, it is known the traditional flow rate prediction (equation 2) is in error. However, as we can also predict the flow rate independently via the correctly measured recovered DP (equation 3) and also independently via the correctly measured PPL (equation 4) the actual flow rate can be found. Furthermore, as we know from the diagnostic result that the recovered and PPL DP's are correct, we can infer the true traditional DP via equation 1 and then predict the correct flow rate from equation 1 using the inferred traditional DP. This also means the size of the error induced by the DP transmitter can be found. It also means, as the true flow rate can still be metered, there is no critical requirement for immediate maintenance. The meter is still operational (albeit with slightly increased uncertainties on the flow rate prediction) until such time as it suits the operator to carry out the required maintenance.

This example is for the case of a traditional DP transmitter being saturated. However, similar examples can be produced for any of the DP transmitters suffering any type of malfunction. The DP reading diagnostic is very simple but extremely powerful.

5. Orifice Meters & Wet Gas Flow

The orifice meter is the most popular wet gas flow meter in the natural gas production industry. All gas flow meter types are adversely affected by the presence of liquids in gas flows. The orifice meter is no exception. Liquid presence with a gas flow will induce an orifice meter gas flow prediction error.

In the last 20 years the orifice meter has received some bad publicity where it has been claimed the orifice meter is a relatively poor wet gas meter. However, in recent years it has been realized that these claims are not entirely fair and in fact there is much to commend the orifice meter as relatively sound meter choice for economic wet gas flow metering applications. In order to discuss the orifice meters reaction to wet gas flow it is first necessary to review the terminology used.

5a. Wet Gas Flow Parameters

The term 'liquid loading' is often used as a qualitative term to describe relative liquid content of a wet gas flow. There are many parameters that can be used to quantify the relative amount of liquid relative to a unit quantity of gas. This paper uses one of the most popular, the Lockhart-

Martinelli parameter (X_{LM}). This is found by equation 9. Note that m_g and m_l are the gas and liquid mass flow rates and ρ_g and ρ_l are the gas and liquid densities respectively. The Lockhart-Martinelli parameter has a complex and long history. This discussion is outside the scope of this paper but the interested reader can find a detailed discussion on this and other wet gas flow parameters in the ASME report 19G [4]. For this discussion it is sufficient to consider the Lockhart-Martinelli parameter a measure of the 'wetness' of a wet gas flow.

$$X_{LM} = \frac{m_l}{m_g}\sqrt{\frac{\rho_g}{\rho_l}} \quad \text{--- (9)}$$

An orifice meter's response to wet gas flow is dependent on the gas to liquid density ratio, *DR* (i.e. the pressure for given fluids at a set temperature). See equation 10.

$$DR = \rho_g / \rho_l \quad \text{--- (10)} \qquad Fr_g = \frac{m_g}{A\sqrt{gD}}\sqrt{\frac{1}{\rho_g\left(\rho_l - \rho_g\right)}} \quad \text{--- (11)}$$

An orifice meter's response to wet gas flow is dependent on the gas densiometric Froude number, Fr_g, i.e. the gas flowrate for given pipe size and fluid properties. See equation 11. Note that '*A'* denotes the inlet area and 'g' is the gravitational constant.

An orifice meter's response to wet gas flow is independent of gas composition but dependent on liquid properties. In natural gas production the liquid tends to be water, light hydrocarbon liquid ('HCL') or a mix of these liquids. The '**W**ater **L**iquid **R**atio', (WLR) describes the relative amount of water and HCL. The WLR is defined by equation 12. Note that Q_w and Q_{hcl} are the gas and water volume flowrates at flowing conditions respectively. However, the orifice meter wet gas correction factor discussed below uses a modified version of this term, the mass WLR. The mass WLR is defined by equation 13. Note that m_w and m_{hcl} are the gas and water mass flow rates.

$$WLR = \frac{Q_w}{Q_w + Q_{hcl}} \quad \text{--- (12)} \qquad WLR_m = \frac{m_w}{m_w + m_{hcl}} \quad \text{--- (13)}$$

When the liquid is a mix of water and HCL an average liquid density ($\rho_{l,hom}$) is used. This is calculated by equation 14. Note that ρ_w and ρ_{hcl} are the water and HCL densities respectively.

$$\rho_{l,\text{hom}} = \frac{\rho_w \rho_{hcl}}{\left(\rho_{hcl} WLR_m\right) + \rho_{w_1}\left(1 - WLR_m\right)} \quad \text{--- (14)}$$

$$OR = \frac{m_{g\,apparent}}{m_g} \quad \text{--- (15)} \qquad OR\% = \left(\frac{m_{g\,apparent}}{m_g} - 1\right) * 100\% \quad \text{--- (15a)}$$

When the gas flow is wet (i.e. $X_{LM} > 0$), the orifice meter gas mass flowrate prediction has a bias. This uncorrected gas mass flow rate prediction is termed the 'apparent' gas mass flow rate ($m_{g,apparent}$). The ratio of the measured (apparent) gas mass flow rate to the actual gas mass flow rate (m_g) is termed the 'over-reading' (denoted by OR, as shown in equation 15). It is common for the over-reading to be presented as a percentage, as shown in equation 15a.

5b. Comments on Orifice Meters with Wet Gas Flow

The dispersion of the liquid in the gas is called the 'flow pattern' (or the 'flow regime'). The flow pattern is dependent on many factors including the meter orientation, gas to liquid density ratio (i.e. pressure), the gas velocity (i.e. gas densiometric Froude number), the relative liquid to gas flow (i.e. the Lockhart-Martinelli parameter) and the liquid properties. The flow pattern dictates the orifice meters response to wet gas flow.

Most orifice meters are installed in the horizontal orientation, e.g, see Fig 21. (Note that for wet gas flow flooding of the impulse lines is a concern so orifice meters knowingly installed in wet gas flow applications often have pressure ports at top dead center only, e.g. Fig 21.)

There are three common flow patterns for horizontal wet gas flow, stratified flow, annular mist flow and slug flow, although in reality wet gas flows are often a mix of these flow patterns. Fig 22 shows a picture of a CEESI view port. Figs 23a, 23b & 23c show stills from video footage recorded by this CEESI view port / camera system on a 4" horizontal wet gas flow.

Fig 21. Wet gas flow test of an orifice meter with pressure taps at top dead centre.

Fig 22. CEESI 4" Spool with View Port & Camera.

Fig 23a. Gas/HCL stratified. Fig 23b. Gas/HCL transition. Fig 23c.Gas/HCL annular.

Fig 23a shows stratified flow (sometimes called 'separated' flow). This is the likely flow pattern at low pressure and / or low gas velocity. The gas has little energy (i.e. low gas dynamic pressure) to drive the liquid and the liquid weight is the dominant force. The liquid flows at the base of the pipe like a river, driven by the interfacial shear stress.

Fig 23c shows annular mist flow (also called 'mist' or 'dispersed' flow). This is the likely flow pattern at high pressure and / or high gas velocity. The gas has a lot of energy (i.e. a high gas dynamic pressure) to drive the liquid and the liquid weight is a relatively small force in comparison. The liquid flows as droplets entrained in the gas, with a film of liquid on the pipe wall. In many wet natural gas production flows the flow conditions are such that the flow pattern is a hybrid (i.e. in transition) between stratified and annular mist flows. Fig 23b shows such a transition flow.

Slug flow (not shown) is an unstable flow that consists of intermittent columns of liquid (called 'slugs'). It is common with low pressure and / or low velocity flow conditions coupled with a high liquid loading. It is not advisable to attempt to meter wet gas flow when slug flow exists as the flow is highly unsteady and therefore the corresponding DP's are highly unsteady.

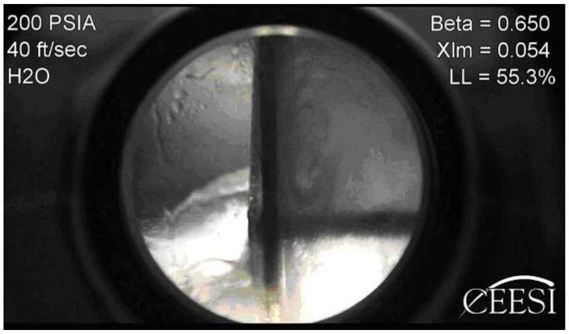

Fig 24a.Stratified flow approaching plate

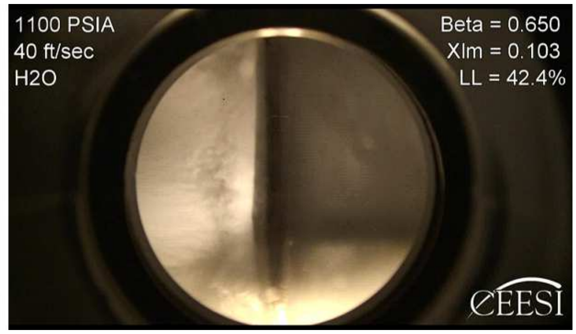

Fig 24b.Annular Mist flow approaching plate

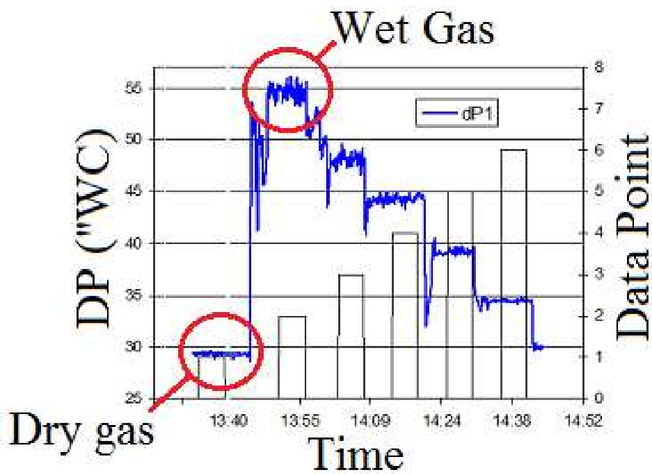

Fig 25. CEESI wet gas flow test data for a 4", 0.5 beta ratio orifice meter, six liquid loadings.

It is sometimes assumed that an orifice plate acts as a dam with wet gas flows and is therefore not suitable as a wet gas meter. However, this is not true. An orifice plate does not dam significant quantities of liquid. It cannot. With a given steady mass flow of gas and liquid the conservation of mass must hold. If liquid begins to dam up the available cross sectional area for the oncoming flow reduces and the flow accelerates increasing the local dynamic pressure and therefore driving more liquid through. For any wet gas flow condition the system must come to an equilibrium where all the on-coming gas and liquid flows through the meter. Damming is a non-issue. Figures 24a & 24b (where flow is left to right) show stills from video footage taken at CEESI. Here an orifice plate has been located in the centre of the view port (with a bar holding it in place). Both stratified and annular mist flow were filmed. The wet gas flow conditions were held constant for 20 minutes at a time. No damming was ever seen to occur.

With wet gas flow through orifice meters, liquid will become entrained in the recirculation zone downstream of the plate (e.g. see Figs 24a & 24b). It has been suggested that with the low pressure port in this vicinity the DP's must be unstable and therefore the orifice meter cannot be suitable for wet gas flow applications. However, again this is not the case. Figure 25 shows actual raw DP data from an orifice meter operating initially with dry gas flow. The average dry gas DP is approximately 29.5"WC, but clearly this is the average of DP's that vary slightly around that value. That is, the dry gas flow DP has a slight 'bounce', a small finite standard deviation. Figure 25 then shows the same meter with the same gas flow conditions but with a series of six liquid loadings (i.e. data point 1 to 6, X_{LM} of 0, 0.25, 0.2, 0.15, 0.1, 0.05 respectively). The wet gas flow causes both the DP and the standard deviation to increase markedly. Therefore, the DP does indeed have more of a 'bounce' (i.e. higher standard deviation) with wet gas flow. However, this does not matter. The fact that the DP signal has a higher standard deviation has no practical draw backs. The averaged DP is still very reproducible.

5c. Orifice Meter Quantitative Response to Wet Gas Flow

Liquid presence in the gas flow tends to induce a positive bias (or 'over-reading') on the orifice meter gas flow rate prediction. The larger the Lockhart-Martinelli parameter value, the larger the over-reading (see Fig 26). Note, that for extremely low liquid loadings the liquid induced gas flow rate prediction bias can be slightly negative (see Ting [5]). This is not accounted for by orifice meter wet gas correlations.

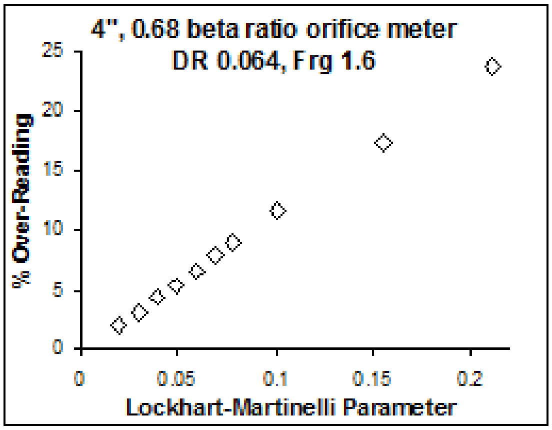

Fig 26. Liquid Loading Effect.

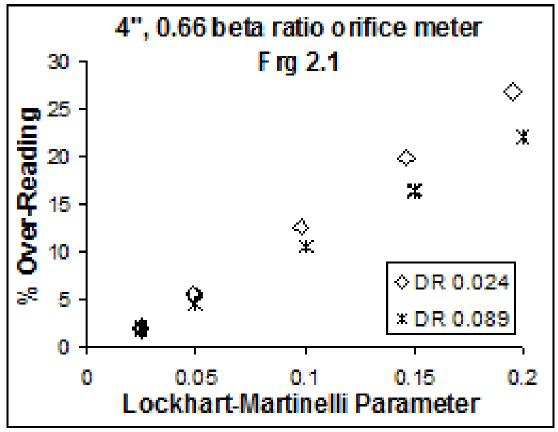

Fig 27.Gas to Liquid Density Ratio Effect.

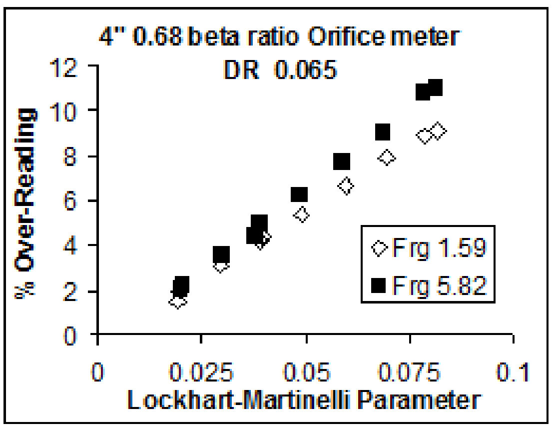

Fig 28.Gas Densiometric Froude No. Effect.

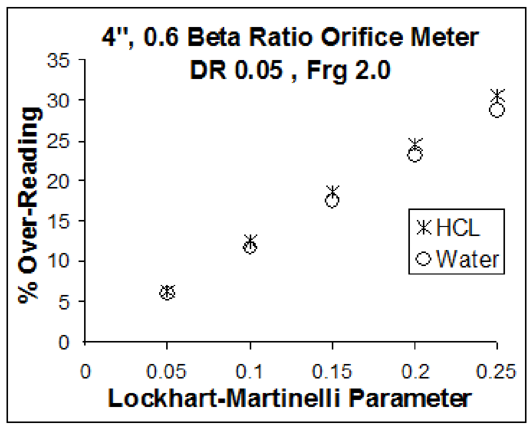

Fig 29. Liquid Property Effect.

The gas to liquid density ratio affects the over-reading. For all other wet gas flow parameters held constant an increasing gas to liquid density ratio reduces the wet gas over-reading (see Fig 27). The gas densiometric Froude number affects the over-reading. For all other wet gas flow parameters held constant an increasing gas densiometric Froude number increases the wet gas over-reading (Fig 28). The liquid properties affect the over-reading. For all other wet gas flow parameters held constant, water based wet gas flows tend to have lower over-readings than hydrocarbon liquid (HCL) based wet gas flows (see Fig 29).

Meter orientation (i.e. flow horizontal, vertical up, vertical down or inclined) has a very significant influence on a wet gas flow pattern, and hence, on an orifice meters wet gas over-reading. Most orifice meters are installed in horizontal installations and the available orifice meter wet gas flow correction factors tend to be for horizontal flow only. It is not advisable to apply wet gas correlations to orifice meters installed in orientations other than those they were created for.

It is known that the beta ratio influences an orifice meters wet gas over-reading. However, the effect is small and considered no greater than the uncertainty in the available data and data fitting techniques. Hence, the beta ratio effect is ignored by the wet gas correlations.

There is no published evidence that different orifice meter tap configurations cause a change in wet gas flow performance, although the vast majority of the public data is taken from orifice meters with flange taps.

The most recent and comprehensive orifice meter wet gas correction factor was released by Steven et al [6]. It is reproduced here are equation set 9, 11, 13, 14, 16 thru 22b. It will be immediately noticed that this correction factor is complicated. Much as it is desirable to keep the technology as simple as possible for the user the orifice meters reaction to multiphase wet gas flow is relatively complex. The correction factor must account for all the various wet gas parameter influences on the meters gas flow prediction bias.

$$m_{l,total} = m_w + m_{hcl} \quad \text{--- (16)}$$

$$WLR_m = \frac{m_w}{m_{l,total}} \quad \text{--- (13)}$$

$$\rho_{l,\hom} = \frac{\rho_w \rho_{hcl}}{(\rho_{hcl} WLR_m) + \rho_{w_1}(1 - WLR_m)} \quad \text{--- (14)}$$

$$\dot{m}_g = \frac{\dot{m}_{g,apparent}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \quad \text{--- (17)}$$

$$C = \left(\frac{\rho_g}{\rho_{l,\hom}}\right)^n + \left(\frac{\rho_{l,\hom}}{\rho_g}\right)^n \quad \text{--- (18)}$$

$$X_{LM} = \frac{m_{l,\hom}}{m_g}\sqrt{\frac{\rho_g}{\rho_{l,\hom}}} \quad \text{--- (9)}$$

$$Fr_g = \frac{m_g}{A\sqrt{gD}}\sqrt{\frac{1}{\rho_g(\rho_{l,\hom} - \rho_g)}} \quad \text{--- (11)}$$

$$Fr_{g\,strat} = 1.5 + (0.2 * WLR_m) \quad \text{-- (19)}$$

$$\#A = 0.4 + \{-0.1 * (\exp(-WLR_m))\} \quad \text{-- (20)}$$

$$n_{strat} = \left\{\left(\frac{1}{\sqrt{2}}\right) - \left(\frac{\#A}{\sqrt{Fr_{g,strat}}}\right)\right\}^2 \quad \text{-- (21)}$$

$$n = n_{strat} \quad \text{for } Fr_g \le Fr_{g,strat} \quad \text{-- (22a)}$$

$$n = \left(\left(\frac{1}{\sqrt{2}}\right) - \left(\frac{\#A}{\sqrt{Fr_g}}\right)\right)^2 \quad \text{for } Fr_g > Fr_{g,strat} \quad \text{-- (22b)}$$

To apply the correction factor certain input information is required. It is necessary to know the gas, water and HCL densities. The fluid properties are widely accepted as required inputs in most flow meters. However, note that unlike single phase flows, such information is not necessarily easy to find in multiphase wet gas flows. Compared to single phase flow sampling, sampling multiphase wet gas flows is "…more challenging". The sampler has to assure that the sample has caught all the various components that are in the flow. Subsequent analysis occurs at atmospheric conditions. Is there a phase change between flow and atmospheric conditions? Knowing fluid properties of a multiphase wet gas flow is not trivial. Further discussion is beyond the scope of this paper but the reader should be aware of this difficulty.

It is necessary to know the water and HCL flow rates. The orifice meter is not a "wet gas flow meter", i.e. it does not meter gas and liquid flow rates. Such meters exist (with hotly debated uncertainties) but they cost an order of magnitude more than the humble orifice meter. To use an orifice meter with multiphase wet gas flow the operator must either except the gas flow rate prediction bias induced by the liquids or correct for it. The correction factor requires the water and HCL flow rates be supplied from an external source. There are ways and means of obtaining

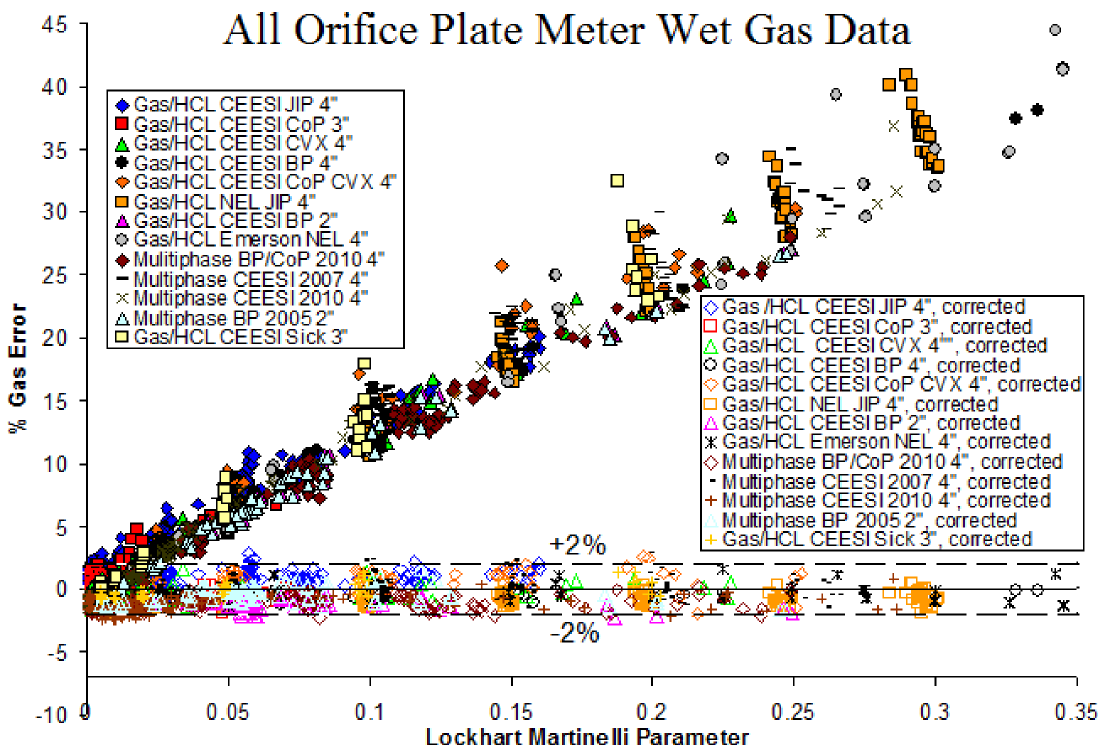

Fig 30. All 2" to 4" orifice meter wet gas data with and without correction.

such estimates, such as test separator histories. However, these are spot checks. Once the water and HCL flow rates are predicted, these input values remain constant in the correlation until they are replaced by updated information, i.e. a new spot check is carried out.

With known fluid densities and liquid flow rates the correction factor can be applied. The gas, water and HCL densities along with the total liquid flow rate (equation 16) and the mass WLR (equation 13) are substituted into equations 9,11,14,18 thru 22b. This leaves one unknown in the equation set, i.e. the actual gas mass flow rate. The solution to this equation set requires an iteration on the actual gas mass flow rate. Such is the unavoidable complexity of this correction factor that it is recommended that flow computers should have this correlation available and double checked, rather than individual engineers attempting to apply it with their own software. However, the correction is new and as yet not included in any flow computer.

The result of applying this correction to massed 2", 3" & 4" orifice meter wet gas flow data sets (of various beta ratios) owned by multiple companies, recorded over several years at different test facilities is shown in Figure 30. Across the substantial wet gas flow range of $X_{LM}<0.35$ the uncorrected liquid gas flow rate prediction error can reach as high as 40%. However, for known water and HCL flow rates and fluid densities the gas flow prediction can be corrected to 2% uncertainty at 95% confidence. For more details on orifice meter reaction to wet gas flow and the applicability of this correlation see Steven [5].

6. <u>Orifice Meter Diagnostics and Wet Gas Flow</u>

An orifice meters integrity is entirely dependent on the read DP's being trustworthy. However, wet gas flow is an adverse flow condition for DP transmitters. Wet gas flow produces significantly higher DP's to when that gas flow is dry. As such over-ranging (or 'saturating') the DP transmitters is a common problem with wet gas flow. A saturated DP transmitter does not supply the correct DP produced by the meter, but rather the erroneous value of the transmitters upper range limit. Also, 'steady' wet gas flows are by nature only pseudo-steady. The combination of relatively high DP standard deviations and / or periodic slugging causing sudden DP spikes can cause the DP transmitters to prematurely drift. For these reasons, wet gas flow is a challenging application for DP transmitters, and yet the problem is widely ignored by operators. The problem of DP reading integrity is 'the elephant in the room' when operators discuss wet gas metering with orifice meters. Without trust in the DP values the traditional approach of using an orifice meter with a wet gas flow correlation is undermined. Erroneous DP values entered into any correction factor produce erroneous results. The largely unspoken truth is that without a method of checking the correctness of the DP's the wet gas flow orifice meter system is being run on a faith based basis.

The DP meter diagnostics described above monitor the DP readings. As equation 1 is a consequence of the first law of thermodynamics it cannot be violated. Wet gas flow cannot cause an orifice meter system to violate equation 1. That is, the diagnostics DP reading check works for wet gas applications just as it does for dry gas flow applications. Figure 32 shows a real diagnostic result from a horizontally installed 4", sch 40, 0.683 beta ratio orifice meter with wet gas flow. Note that the DP check, i.e. point (x_4,0) shows that the DP readings are correct even though the wet gas flow has affected the other diagnostic points.

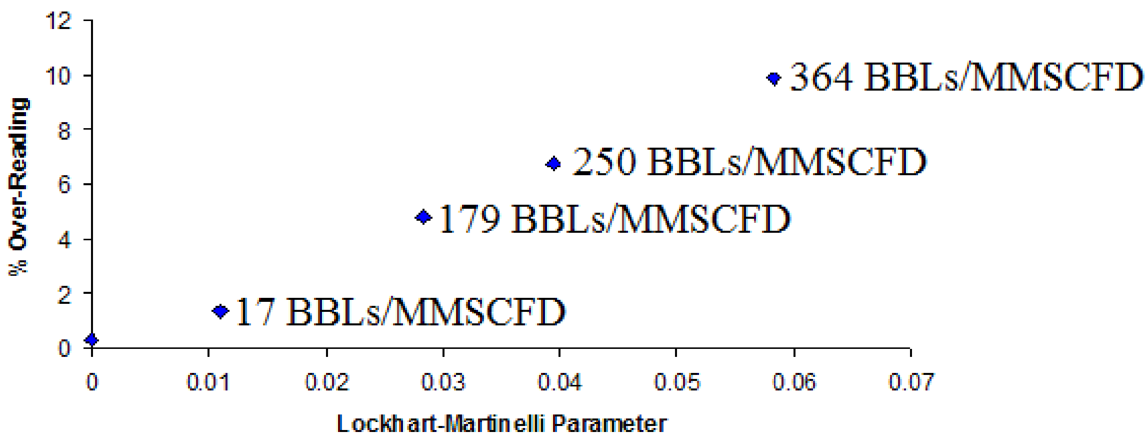

Figure 31. 4", sch 40, 0.683 beta ratio orifice meter data, 204psi(a), 4 MMSCFD.

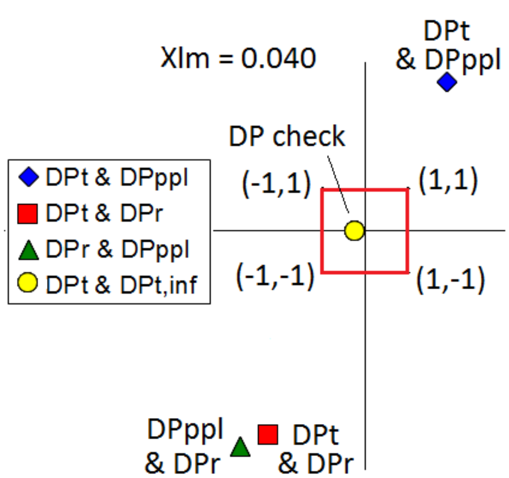

Fig 32. 4", 0.683β Orifice Meter Wet Gas Flow Diagnostic Result for Xlm 0.04, DR 0.0135, Frg 1.4.

Fig 31 shows CEESI wet gas flow data from a 4", sch 40, 0.683 beta ratio orifice meter. The wet gas flow conditions were natural gas and HCL at a gas to liquid density of 0.0135 and gas densiometric Froude number of 1.40. The meter installation is shown in Fig 21. Fig 32 shows the diagnostic response to the particular case shown in Fig 31 of a Lockhart-Martinelli parameter of 0.04. The over-reading is approximately +7%. Note, the along with the DP check, i.e. (x_4,0), showing that the DP's are being read correctly, the traditional to PPL DP pair point, i.e. (x_1,y_1), is in the 1st quadrant, while the traditional to recovered DP pair and the PPL and recovered DP pair, i.e. (x_2,y_2) & (x_3,y_3), are together in the third quadrant. This is the particular orifice meter diagnostic pattern created by wet gas flow.

The higher the Lockhart-Martinelli parameter the further from the NDB the points are. Fig 33 shows all diagnostic results for the data shown in Figure 31 superimposed together. All DP

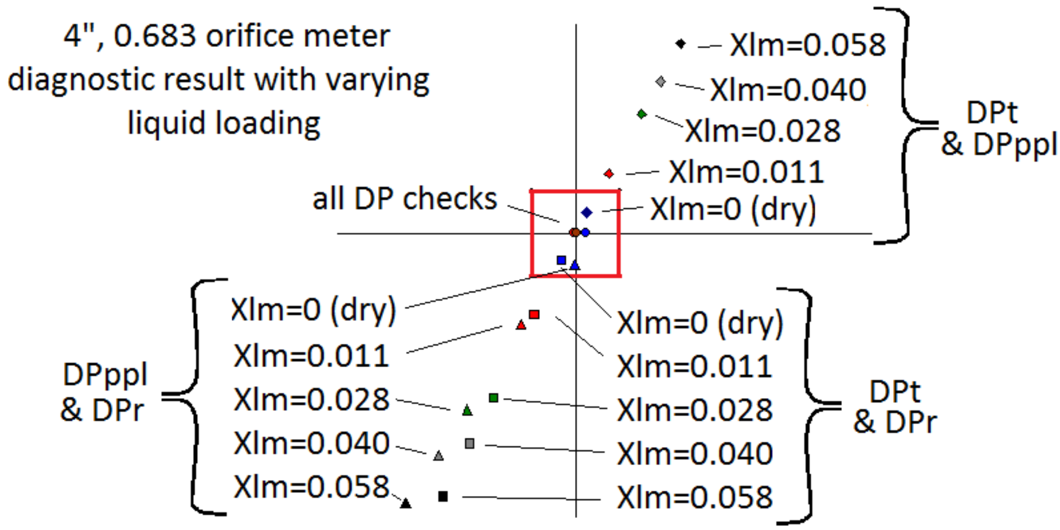

Fig 33. All Diagnostic results from data shown in Figure 31.

reading integrity checks, i.e. $(x_4,0)$, are superimposed on top of each other inside the NDB showing the DP's were always read correctly for all wet gas flow conditions. All four dry gas flow diagnostic points are within the NDB as expected. As the Lockhart-Martinelli parameter increases point (x_1,y_1) moves into the first quadrant while the points (x_2,y_2) & (x_3,y_3) move into the third quadrant. Therefore, for a known metering problem, e.g. wet gas flow, the diagnostic co-ordinates can give qualitative information to the scale of the problem, i.e. in this case the wetness of the gas. The further the diagnostic points from the NDB the bigger the problem, i.e. in this case the wetter the gas.

Section 2 gives a description of a method of presenting the diagnostic results. In this form of presentation the diagnostic parameters were 'normalised' by dividing their 'raw' output (i.e. $\psi\%$, $\lambda\%$, $\chi\%$, $\alpha\%$, $\gamma\%$ & $\eta\%$) by a set associated uncertainty (i.e. $\phi\%$, $\xi\%$, $\upsilon\%$, a%, b% & c%). This normalisation procedure is utilised when monitoring an orifice meter in single phase flow service for general problems as it helps avoid false alarms. However, it does reduce the sensitivity of the diagnostics if they are being used to monitor changes in a given / known problem. The normalization procedure dictates each diagnostic parameters sensitivity. The diagnostics maximum diagnostics sensitivity is set by not normalizing the data, i.e., using the 'raw' diagnostic results (i.e. $\psi\%$, $\lambda\%$, $\chi\%$, $\alpha\%$, $\gamma\%$ & $\eta\%$). When monitoring a known problem (such as the liquid loading of a wet gas flow) the smallest changes are shown by the raw diagnostic results. Figures 34 thru 35a show two examples of the orifice meter diagnostics set at maximum sensitivity with wet gas flows.

Figures 34 shows 'un-normalised' wet gas flow data taken at CEESI from an 8", schedule 40, 0.689β orifice meter. The constant gas flow of 9.5 MMSCFD was set at a pressure of 224 psi(a). The diagnostics co-ordinates plotted on the dimensionless graph are ($\psi\%$, $\alpha\%$), ($\lambda\%$, $\gamma\%$) & ($\chi\%$, $\eta\%$). Figure 34a shows the same data presented in a different format. The liquid loading is shown in terms of barrels (BBLs) per million standard cubic feet (MMSCF). Figures 35 shows 'un-normalised' wet gas flow data taken at CEESI from a 4", schedule 40, 0.624β orifice meter. The gas flow was between 13 & 17 MMSCFD. The pressure was 479 psi(a). Again, the diagnostics co-ordinates plotted on the dimensionless graph are ($\psi\%$, $\alpha\%$), ($\lambda\%$, $\gamma\%$) & ($\chi\%$, $\eta\%$). Figure 35a shows the same data presented in a different format. The liquid loading is shown in terms of barrels (BBLs) per million standard cubic feet (MMSCF). In these plots the NDB is not applicable and is therefore not present. In this scenario of there being a known single source of the orifice meters problem, i.e. wet gas flow, if the points drift further from the graph's origin the gas is getting wetter, if the points drift towards the graph's origin the gas is getting drier.

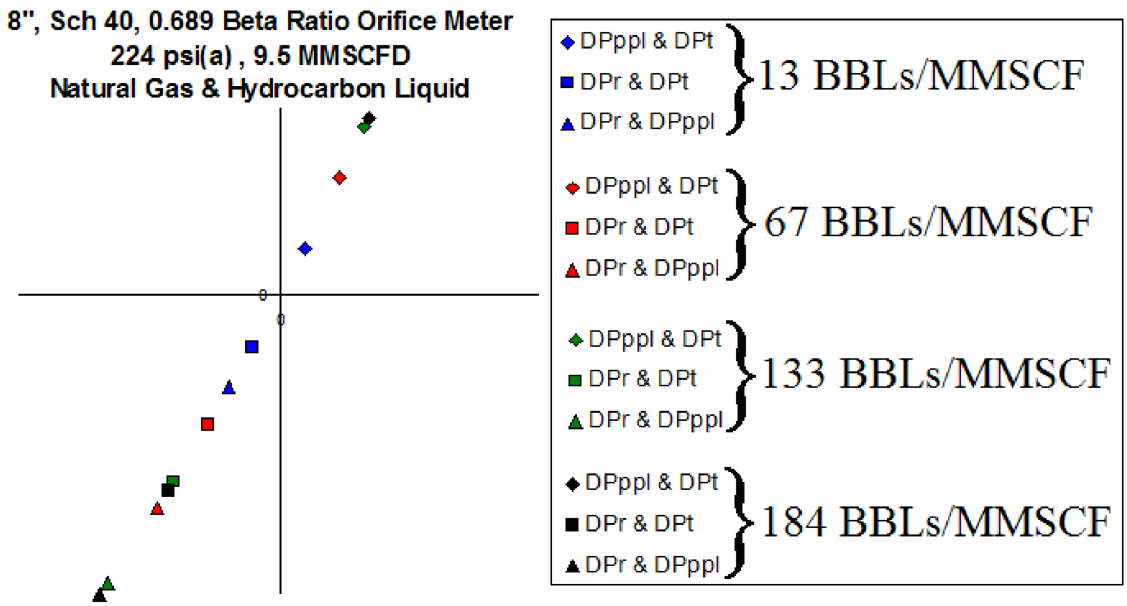

Fig 34. 8", 0.689β Orifice Meter, 224 psi(a) & 9.5 MMSCFD, No Normalization of Data.

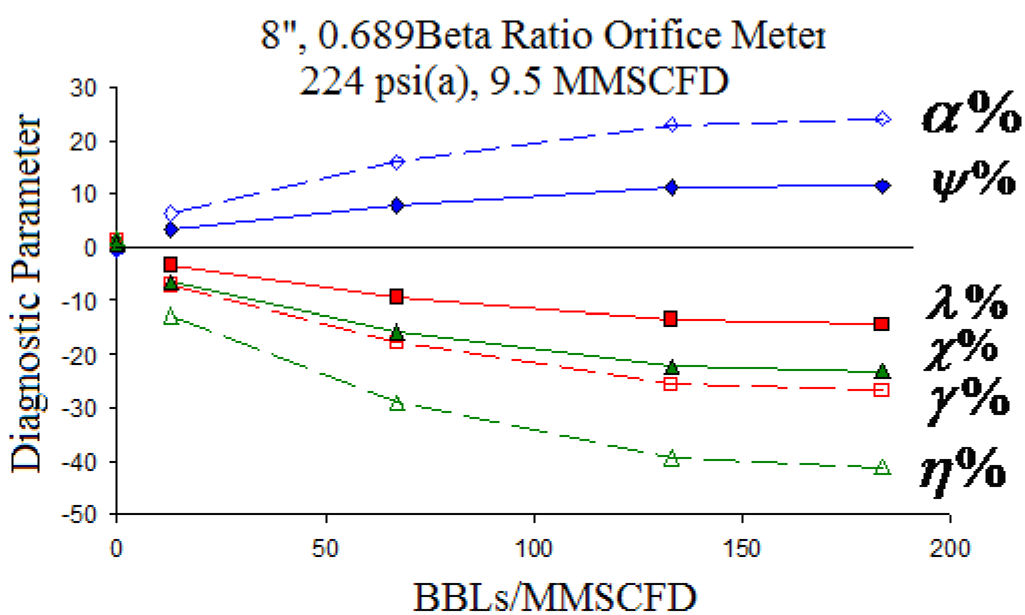

Fig 34a. 8", 0.689β Orifice Meter, 224 psi(a) & 9.5 MMSCFD, Diagnostic Parameters vs. Liquid Loading.

The industries standard periodic liquid flow rate spot checks required when using an orifice meter with a wet gas correlation are relatively time consuming and expensive. If there has been no change in liquid flow rates this procedure is a needless expense. On the other hand if the liquid flow rate is found to have changed the orifice meter wet gas flow over-reading correction gets updated but there is still no way of knowing ***when*** the liquid flow rate changed between these spot checks. Traditionally therefore, there is no way of re-allocating incorrectly measured gas flow due to liquid loading changes between spot checks. Effectively, due to lack of viable alternatives, the standard procedure has been to run the system blind to the liquid loading, hope the liquid loading doesn't change and take a glance at the liquid flow rate periodically (at usually ≥ 6 month intervals). Hence, a real time indication of an increasing or decreasing liquid to gas flow rate ratio is greatly desirable.

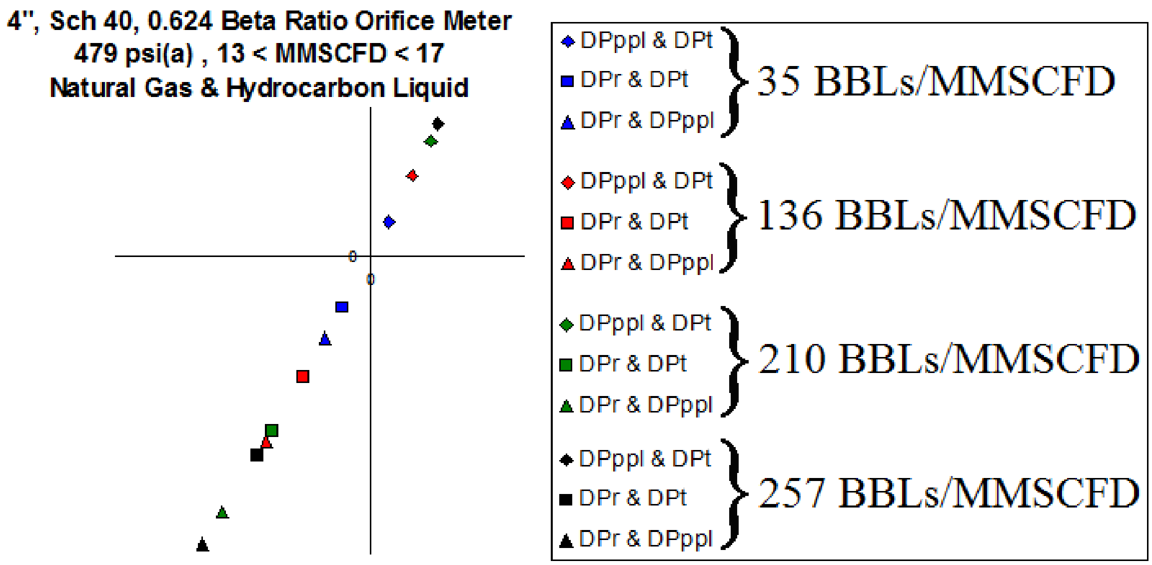

Fig 35. 4", 0.624β Orifice Meter, 479 psi(a) & 13 to 17 MMSCFD, No Normalization of Data.

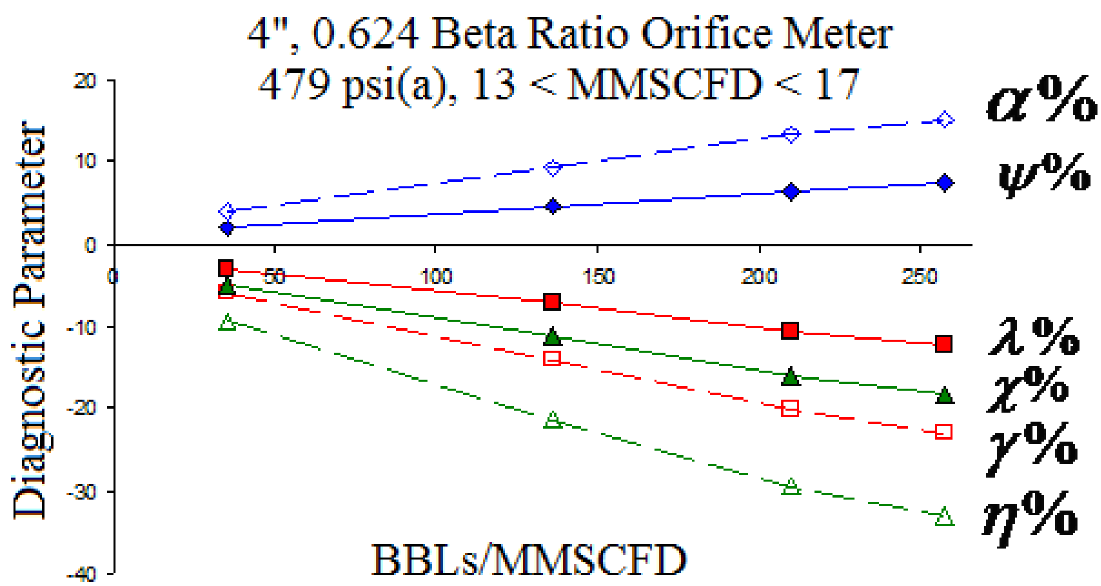

Fig 35a. 4", 0.624β Orifice Meter, 479 psi(a) & 13 to 17 MMSCFD, Diagnostic Parameters vs. Liquid Loading.

Figs 34 thru 35a clearly show that monitoring the diagnostics can clearly indicate increases and decreases in the wet gas flows liquid loading. However, whereas the diagnostic plot (as shown in Figures 34 & 35) can indicate changes in liquid loading, it is possible to make the diagnostic output more user friendly. If the operators were to use the diagnostic output as shown in Figures 34 & 35 they would have to be diligent and check averaged co-ordinate values over time for changes. However, there is an easier, method of monitoring liquid loading changes. The diagnostics can be 'zeroed' to a particular flow condition. This places the points in the NDB (for the case of using normalised diagnostic data), or at the graph's origin (for the case of using 'raw' diagnostic data) for a given wet gas flow condition. If the liquid loading changes, the points will diverge thereby alerting the meter operators to the change in liquid loading.

6a. Zeroing the Diagnostics

The diagnostic baseline can be changed from the ISO stated performance to any arbitrary assigned performance, e.g. the performance the meter happens to have at any given time. After this act of 'zeroing', the diagnostic system monitors the performance of the metering system compared to that baseline, i.e. the performance of the meter at the time of zeroing the diagnostics. This allows any trending to be easily seen. For example, take the case of wet gas flow. Wet gas flow causes the diagnostics to register a meter problem (e.g. see Fig 32). However, for that particular wet gas flow condition the diagnostics can be 'zeroed', i.e. that wet gas flow condition can be assigned as the diagnostic baseline on which all other future meter performance will be compared. Any subsequent increase or decrease in the liquid loading will change the meters diagnostic output. This makes the zeroing factor applied for the previous liquid loading value incorrect for these new different conditions. The diagnostic points will diverge indicating a change in liquid loading. Such a capability has obvious advantages to the operators that currently rely on periodic portable test separators to check for changes in the gas to liquid flow rates. The 'zeroing' technique is now described.

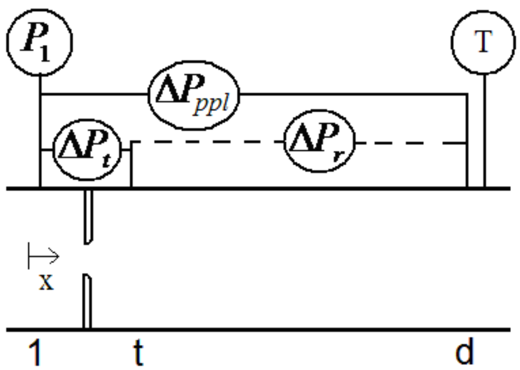

Fig 1a. Orifice meter with downstream tap.

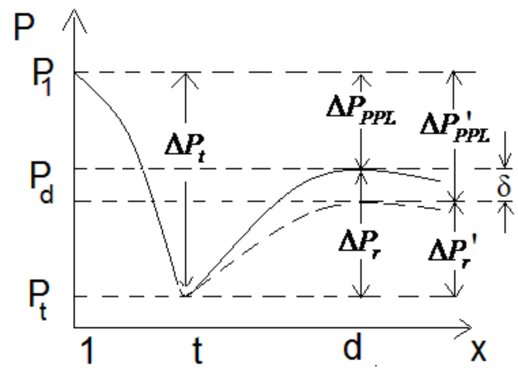

Fig 1b. Arbitrary pressure fluctuation through meter.

Figure 1a represents a generic orifice meter. Fig 1b shows a sketch of two different pressure fields through the generic orifice meter. The solid curved line represents the ISO pressure field prediction for a correctly operating meter producing a given traditional DP (ΔP_t). The dashed curved line represents a pressure field that is caused by a non-standard metering situation producing the same given traditional DP (ΔP_t), such as wet gas flow. Instead of the normal ISO distribution of PPL (ΔP_{PPL}) and recovered DP (ΔP_r) making up a given traditional DP (ΔP_t), the non-standard operating situation has caused this DP distribution to be different. Here we have the given traditional DP split into a different distribution of PPL ($\Delta P'_{PPL}$) and recovered DP ($\Delta P'_r$). Denote the difference in DP's as "δ".

$$\Delta P'_{PPL} = \Delta P_{PPL} + \delta \quad \text{-- (23)} \qquad \Delta P'_r = \Delta P_r - \delta \quad \text{-- (24)}$$

$$\Delta P_t = \Delta P_{PPL} + \Delta P_r = \Delta P'_{PPL} + \Delta P'_r = (\Delta P_{PPL} + \delta) + (\Delta P_r - \delta) \quad \text{-- (25)}$$

$$Z = \delta / \Delta P_t \quad \text{-- (26)}$$

The relationships between the PPL's and recovered DP's for orifice meters operating correctly and orifice meters with 'a problem' are expressed by equations 23 & 24. The relationships between all of these DP's are expressed in equation 25. Let a correction factor (Z) be the ratio of the DP shift (δ) to a given traditional DP (see equation 26). Define the DP ratios of the meter with the 'problem' by equations 27 to 29. Therefore, the new zeroed 'baseline' DP ratios to be used by the meter with 'the problem' are the ISO predictions modified by a correction factor "Z", as shown in equations 30 to 32.

$$PLR^{'} = \frac{\Delta P_{PPL}^{'}}{\Delta P_t} \text{ -- (27)} \qquad PRR^{'} = \frac{\Delta P_r^{'}}{\Delta P_t} \text{ -- (28)} \qquad RPR^{'} = \frac{\Delta P_r^{'}}{\Delta P_{PPL}^{'}} = \frac{PRR^{'}}{PLR^{'}} \text{ -- (29)}$$

$$PLR^{'} = \frac{\Delta P_{PPL}^{'}}{\Delta P_t} = \frac{\Delta P_{PPL}}{\Delta P_t} + \frac{\delta}{\Delta P_t} = PLR + Z \text{ -- (30)}$$

$$PRR^{'} = \frac{\Delta P_r^{'}}{\Delta P_t} = \frac{\Delta P_r}{\Delta P_t} - \frac{\delta}{\Delta P_t} = PRR - Z \text{ -- (31)} \qquad RPR^{'} = \frac{PRR^{'}}{PLR^{'}} \text{ -- (32)}$$

The discharge coefficient remains as the ISO predicted value. However, the recovery coefficient and the PPL coefficient require to be zeroed. Equations 3a & 4a show the expansion and PPL flow equations for the correctly operating meter and for the meter with the problem. Note that the non-standard expansion meter equation introduces a corrected recovery flow coefficient ($K_r^{'}$) to be used with the actual measured recovered DP (i.e. $\Delta P_r^{'}$). Likewise, note that non-standard PPL meter flow equations introduces a corrected PPL flow coefficient ($K_{PPL}^{'}$) to be used with the actual measured PPL (i.e. $\Delta P_{PPL}^{'}$). Equations 3a & 4a can be re-arranged and combined with equations 23, 24, 26, 27 & 28 to produce expressions for the zeroed diagnostics recovered & PPL flow coefficients. Therefore, the new zeroed 'baseline' flow coefficients to be used by the meter with 'the problem' are the ISO based predictions modified by a correction factor "Z", as shown in equations 3b to 4c.

Expansion Flow Equation: $\dot{m}_r = EA_t K_r \sqrt{2\rho \Delta P_r} = EA_t K_r^{'} \sqrt{2\rho \Delta P_r^{'}}$ --(3a)

PPL Flow Equation: $\dot{m}_{ppl} = AK_{PPL} \sqrt{2\rho \Delta P_{PPL}} = AK_{PPL}^{'} \sqrt{2\rho \Delta P_{PPL}^{'}}$ -- (4a)

$$K_r^{'} = K_r \sqrt{\frac{\Delta P_r}{\Delta P_r^{'}}} = K_r \sqrt{\frac{\Delta P_r^{'} + \delta}{\Delta P_r^{'}}} = K_r \sqrt{1 + \frac{\delta}{\Delta P_r^{'}}} = K_r \sqrt{1 + Z \frac{\Delta P_t}{\Delta P_r^{'}}} = K_r \sqrt{1 + \frac{Z}{PRR^{'}}} \text{ --(3b)}$$

$$K_{PPL}^{'} = K_{PPL} \sqrt{\frac{\Delta P_{PPL}}{\Delta P_{PPL}^{'}}} = K_{PPL} \sqrt{\frac{\Delta P_{PPL}^{'} - \delta}{\Delta P_{PPL}^{'}}} = K_{PPL} \sqrt{1 - \frac{\delta}{\Delta P_{PPL}^{'}}} = K_{ppl} \sqrt{1 - Z \frac{\Delta P_t}{\Delta P_{PPL}^{'}}} = K_{PPL} \sqrt{1 - \frac{Z}{PLR^{'}}} \text{ --(4b)}$$

Hence, the application of some correction factor 'Z' can zero the diagnostic response of an orifice meter with 'a problem'. The precise reason for a baseline offset need not be known. The value of Z is bound by -1 ≤ Z ≤ +1. The value of 'Z' can be found in the field with ease. It is calculated by equation 30a, i.e. the actual found PLR (i.e. PLR') minus the known baseline PLR (i.e. PLR).

$$Z = PLR^{'} - PLR \text{ --- (30a)}$$

It should be noted that only physical problems such as damaged orifice plates, contaminated orifice meter runs, wet gas flows etc. can be zeroed. DP reading problems produce DP readings that do not have to adhere to any physical laws and therefore it is not possible to zero such malfunctions.

6b. Zeroing Wet Gas Flow Orifice Meter Diagnostic Results

Figure 32 shows a diagnostic result for a 4", sch 40, 0.683β orifice meter with a wet gas flow with a gas to liquid density rato of 0.0135, a gas densiometric Froude number 1.4 and a Lockhart-Martinelli parameter of 0.04. The associated over-reading, i.e. gas flow rate prediction bias, is 7%. If this situation existed in the field a spot check would confirm the liquid flow rate (of 0.7 lb/s) and an orifice meter wet gas correlation would be applied to correct the gas flow rate prediction.

If these orifice meter diagnostics were included in the system the diagnostic results are as shown in Fig 32 & 32a. (Fig 32a is Fig 32 with the DP check removed for clarity and placed beside Fig 32b for direct comparison). The diagnostics clearly show a metering problem exists. Registering the wet gas flow condition (and finding the liquid flow rate with a spot check) the diagnostic result can then be zeroed. It was found here that Z = +0.0574 zeroed the diagnostic result, as shown in Fig 32b. Fig 32b is the same data as Fig 32a, with the zeoring factor in place. As long as the liquid loading does not change the zeroed diagnostics points will remain in the NDB. However, when the wet gas flows' liquid loading changes the diagnostic points immediately respond.

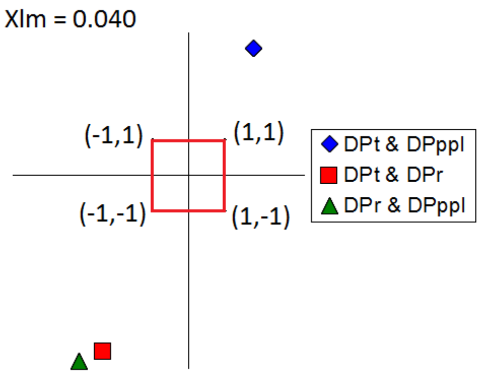

Fig 32a. Diagnostic Result for.
DR 0.0135, Frg 1.4 & Xlm 0.04.

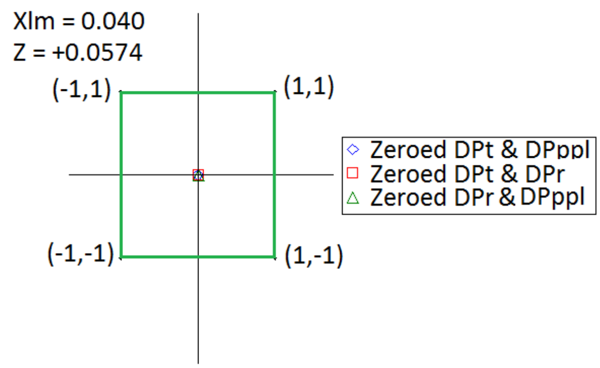

Fig 32b. Zeroed Diagnostic Result for
DR 0.0135, Frg 1.4 & Xlm 0.04.

Figs 32, 32a & 32b show the diagnostic results from the test point at X_{lm} =0.04 in Figure 31. Once the diagnostics are zeroed for X_{lm} =0.04 (Fig 32b) then no problem is indicated. However, what would happen to the diagnostic co-ordinates in Fig 32b if the liquid loading changed?

Say for otherwise set wet gas flow conditions the Lockhart-Martinelli parameter increased from 0.04 to 0.058, i.e. to the higher Lockhart-Martinelli parameter shown in Fig 31 with a liquid flow rate of 1.08 lb/s. The over-reading increases from approximately 7% to 10%. Without a corresponding change to the wet gas correlations entered liquid flow rate value the gas flow prediction will have an approximate +3% bias. However, the appropriate Z factor to zero the diagnostics monitoring such a wet gas flow is +0.0716. With the systems Z-factor still set at +0.0574 the Z-factor is not large enough to zero the diagnostics and a wet gas flow pattern again is seen on the NDB, see Fig 32c. Here then, the diagnostics are showing that there is a problem, and from the pattern it is evident that the liquid loading must have increased.

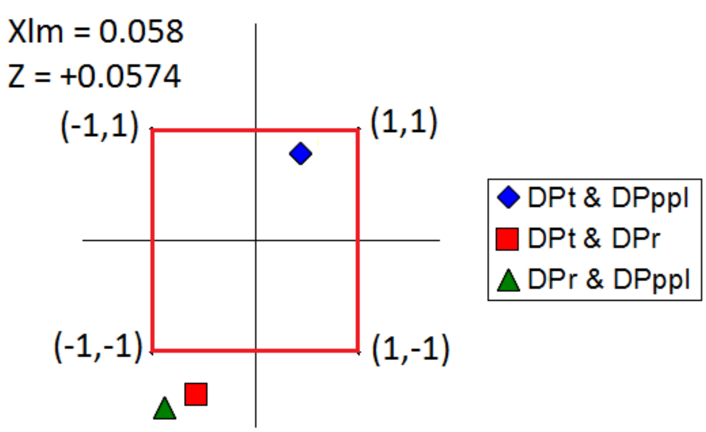

Fig 32c. Diagnostic Result for.
DR 0.0135, Frg 1.4 & Xlm 0.058.

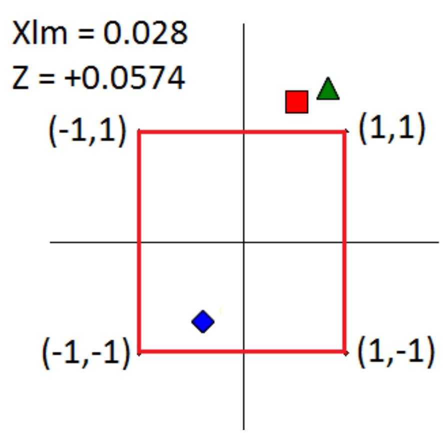

Fig 32d. Zeroed Diagnostic Result for
DR 0.0135, Frg 1.4 & Xlm 0.028.

Say for otherwise set wet gas flow conditions the Lockhart-Martinelli parameter decreased from 0.04 to 0.028, i.e. to the lower Lockhart-Martinelli parameter shown in Fig 31 with a liquid flow rate of 0.53lb/s. The over-reading decreases from approximately 7% to 5%. Without a corresponding change to the wet gas correlations entered liquid flow rate value the gas flow prediction will have an approximate -2% bias. However, the appropriate Z factor to zero the diagnostics monitoring such a wet gas flow is +0.0449. With the systems Z-factor still set at +0.0574 the Z-factor is too large to zero the diagnostic result and the diagnostic pattern shown in Fig 32d is produced. Notice that the reducing liquid loading diagnostic pattern of Fig 32d is the opposite pattern to the increasing liquid loading pattern. Here then, the diagnostics are showing that there is a problem, and from the pattern it is evident that the liquid loading must have decreased.

7. Orifice Meter Beta Ratio Limitations on Wet Gas Flow Liquid Loading Monitoring

By definition, the PLR of an orifice meter must be within the range: $0 \le PLR \le 1$. ISO 5167 Part 2 [3] states that an orifice meters PLR in single phase flow is dictated by the beta ratio (β) and discharge coefficient, C_d, i.e. see equation 33. This equation is the work of Urner [7] and it is wholly theoretical. In this excellent work Urner made several assumptions when deriving equation 33. These assumptions are reasonable and equation 33 works well across much of the ISO orifice meter beta ratio range (i.e. $0.1 \le \beta \le 0.75$). However, at $\beta \ge 0.55$ these assumptions introduce a slight negative bias in the Urner PLR equation.

Figure 36 shows a massed orifice meter PLR vs. beta ratio data set from multiple labs. The Urner equation and a simple data fit (equation 34) are also shown. It was found that the Urner theoretical PLR equation was excellent (and effectively gave the same results as the data and the data sets) for $\beta \le 0.55$. However, at $\beta > 0.55$ a slight negative bias appears. It is therefore advised that the Urner equation be used for $\beta \le 0.55$ and this data fit be used for $\beta > 0.55$. The diagnostics results shown in section 6 used the ISO 5167 discharge coefficient (RHG) equation (see [3]) in conjunction with the PLR equation 34 to derive all the diagnostic parameters.

$$PLR = \frac{\sqrt{1-\left\{\beta^4\left(1-C_d^2\right)\right\}}-C_d\beta^2}{\sqrt{1-\left\{\beta^4\left(1-C_d^2\right)\right\}}+C_d\beta^2} \quad \text{--- (33)}$$

$$PLR = 1.033 + \left(-0.8552 * \beta^{1.5}\right) \quad \text{--- (34)}$$

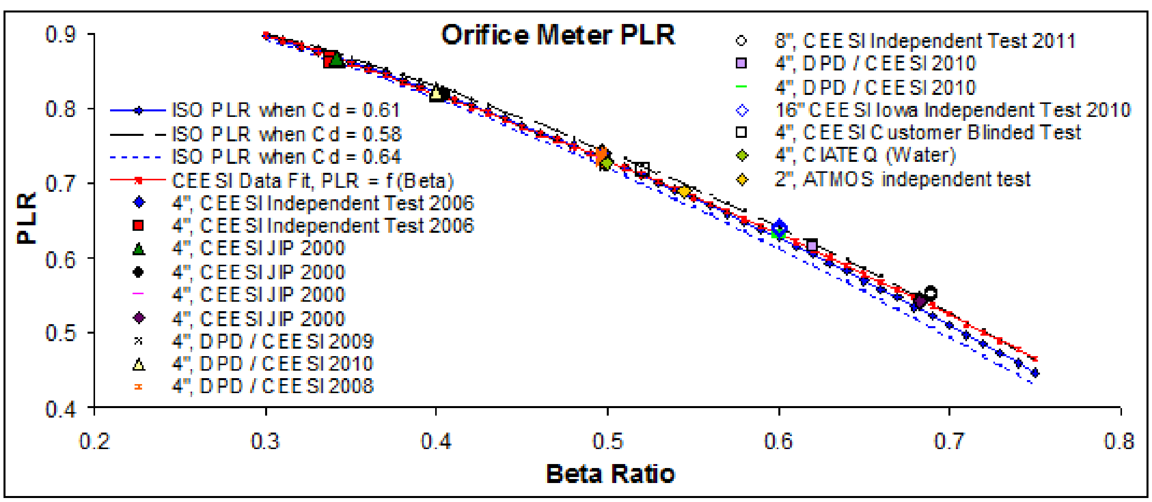

Fig 36. Comparison of the ISO Orifice Meter PLR Prediction with Independent Data.

Four 4” orifice meter beta ratio plates (0.34, 0.4, 0.5 & 0.68) were wet gas flow tested at CEESI. Fig 21 shows the test set up. The downstream tap (off screen at 6D behind the plate) was used to measure the permanent pressure loss, and hence the PLR. The PLR vs. X_{LM} data for these four meters at various gas to liquid density ratios is shown in Figures 37 thru 37c. An orifice meters

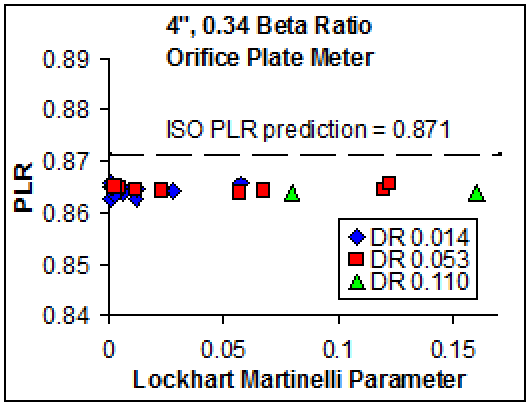

Fig 37.PLR vs. Xlm, 4”, 0.34 beta ratio.

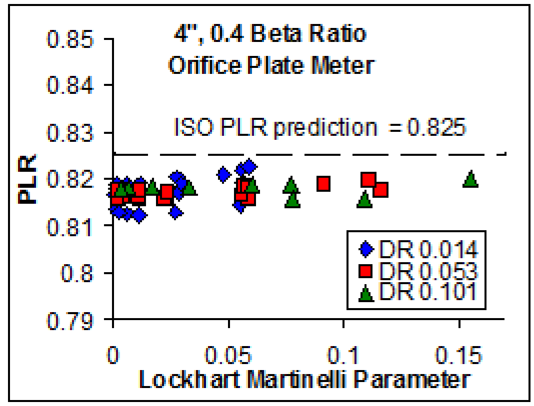

Fig 37a. PLR vs. Xlm, 4”, 0.40 beta ratio.

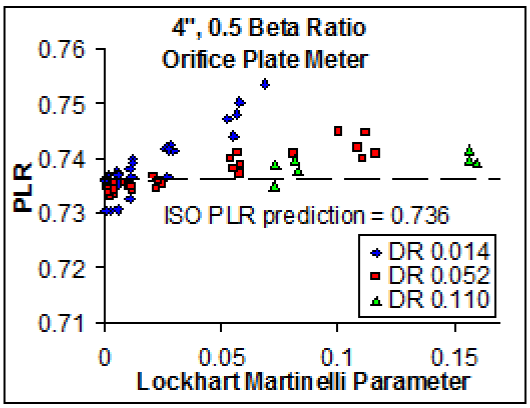

Fig 37b. PLR vs. Xlm, 4”, 0.50 beta ratio.

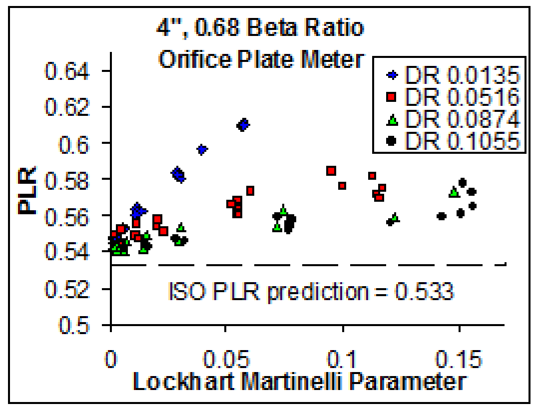

Fig 37c. PLR vs. Xlm, 4”, 0.68 beta ratio.

PLR is extremely dependent on the beta ratio. Fig 36 & equation 33 show that low beta ratio plates produce PLR values with single phase flow that are close to unity. Fig 36 & equation 34 also shows that high beta ratio plates (e.g. β ≥ 0.55) produce PLR values less or equal to 0.68.

The effect wet gas flow has on any differential pressure flow meter, including an orifice meter, is to increase the PLR. However, wet gas flow through an orifice cannot cause the PLR to exceed unity. Hence, when low beta ratio plates are used the single phase flow performance of the plate is already close to the maximum PLR value of unity. Therefore, the wet gas flow has little to no effect on the PLR value, as the wet gas PLR value is sandwiched in the small gap between the single phase PLR value and the PLR value of unity. That is, small beta ratio orifice meters have PLR values insensitive to liquid loading. This is seen in Fig 37 (for 0.34β) & Fig 37a (for 0.40β).

When high beta ratio plates are used the PLR is relatively far from unity, e.g. a 0.683β gives an approximate PLR of 0.54. Therefore, here the wet gas flow has can have a significant effect on the PLR value. That is, high beta ratio orifice meters have PLR values sensitive to liquid loading. This is seen in Fig 37c (for 0.68β). Hence, the diagnostic method described here is designed to be used with moderate to high beta ratio plates only. Furthermore Fig 37b (for 0.50β) & Fig 37c (for 0.68β) also indicate that the gas to liquid density ratio has an effect on an orifice meters PLR value with wet gas flow. The reason for this is well understood but the explanation is well beyond the scope of this paper. For this discussion it is sufficient to note that the gas to liquid density ratio has an effect on the PLR vs. X_{LM} relationship. These orifice meter diagnostics are most sensitive for high beta ratios (user controlled) and for lower gas to liquid density ratio values (application dictated). For this reason DP Diagnostics suggests that if liquid loading monitoring is desired on wet gas orifice meters, β ≥ 0.6 should be selected.

8. Conclusions

Orifice meters remain extremely popular throughout the natural gas production industry. Orifice meter technology is evolving and improving as fast as any other flow meter technology. There has been a sustained series of small improvements in the secondary instrumentation (i.e. the DP transmitters) over the last two decades. A new, very comprehensive, fully disclosed and relatively simple patented orifice meter diagnostic system ('Prognosis') has been disclosed to industry. These diagnostics rival, or exceed, the capability of competing flow meter types. As such, the arrival of orifice meter diagnostics is beginning to be noted in regulatory documents, such as the UK government's DECC Guidance Notes for Petroleum Measurement [8]. With regards to orifice meter maintenance, DECC promote the use of orifice meter diagnostics to facilitate a Condition Based Maintenance (CBM) approach rather than the traditional blind periodic maintenance approach. Similarly, in Canada, ERCB Directive 17 [9] states in Paragraph 2.5.2.1, section 9, regards orifice meters:

"Internal metering diagnostics may be used to determine if the structural integrity of the primary measurement element is within acceptable operating parameters and checked at the same required intervals as an internal inspection. Then internal inspection is not required until an alarm or error is generated by the device or as recommended by the manufacturer. The operator must maintain documentation on the diagnostic capability of the measurement system and make it available to the ERCB on request. An initial baseline diagnostic profile must be performed and documented during the commissioning process."

Finally, research around the world has shown the orifice meter to be a good choice for economic wet gas flow metering. The liquid induced gas flow rate prediction positive bias, or 'over-reading', is known to be very reproducible and therefore predictable. For a known liquid flow rate it is possible to predict the actual gas mass flow rate to 2% uncertainty at 95% confidence. This known liquid flow rate is traditionally obtained from periodic spot checks. Even here, there are significant developments in orifice meter capability. Whereas, the requirement for periodic liquid flowrate checks was an Achilles heel of the orifice meters operational ability with wet gas flow, the new diagnostics ability to continually monitor liquid loading can remove that restriction.

References

1. Steven, R. "Diagnostic Methodologies for Generic Differential Pressure Flow Meters", North Sea Flow Measurement Workshop October 2008, St Andrews, Scotland, UK.
2. Steven, R. "Significantly Improved Capabilities of DP Meter Diagnostic Methodologies", North Sea Flow Measurement Workshop October 2009, Tonsberg, Norway.
3. International Standard Organisation, "Measurement of Fluid Flow by Means of Pressure Differential Devices, Inserted in circular cross section conduits running full", no. 5167, Part 2, 2003.
4. American Society of Mechanical Engineering, MFC, Report 19G, "Wet Gas Metering".
5. Ting V., "Effects of Nonstandard Operating Conditions on the Accuracy of Orifice Meters", Society of Petroleum Engineers Production and Facilities, February 1993
6. Steven et al, "Horizontally Installed Orifice Plate Meter Response to Wet Gas Flows", North Sea Flow Measurement Workshop October 2011, Tonsberg, Norway.
7. Urner, G., "Pressure loss of orifice plates according to ISO 5167", *Flow Measurement and Instrumentation*, **8**, March 1997, pp. 39-41
8. UK Government, Department of Environment and Climate Change: "Guidance Notes for Petroleum Measurement Issue 8", Published 2012
9. ERCB Directive 017: Measurement Requirements for Upstream Oil and Gas Operations (September 2012)