A Diagnostic System for Venturi Meters in Single Phase and Wet Gas Flow Applications

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1. Introduction

Venturi meters are popular for single phase and wet gas flow metering applications. Traditionally the Venturi meter with single phase or wet gas flow has little diagnostic capabilities. However, in the last three years a diagnostic system for generic Differential Pressure (DP) meters has been developed. In this paper this diagnostic system is discussed with the focus particularly on Venturi meters in use with dry and wet gas flows.

2. A Review of the Venturi Meter Diagnostic System

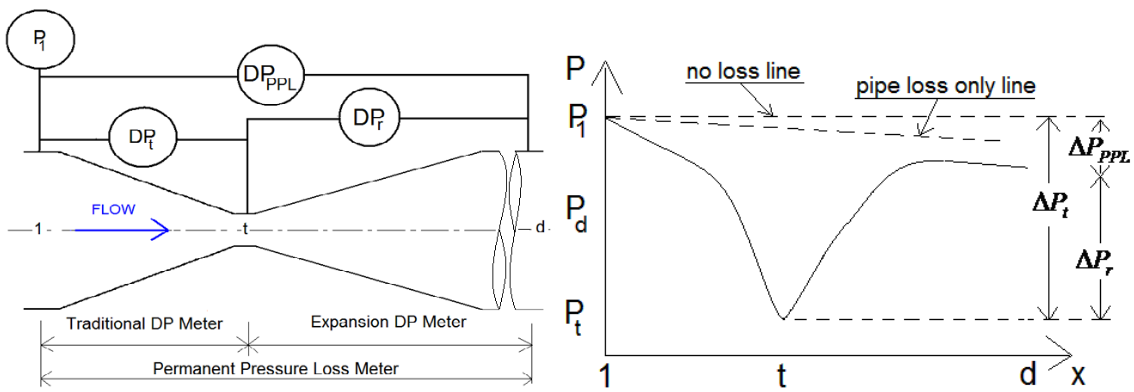


Fig 1. Venturi meter with instrumentation sketch and pressure fluctuation graph

Figure 1 shows a Venturi meter with instrumentation sketch and a simplified sketch of the pressure field produced along the meter body. Traditional Venturi meters read the inlet pressure (P_1), the downstream temperature (T, not shown) and the differential pressure (ΔP_t) between the inlet pressure tap (1) and a pressure tap at the throat, i.e. the point of low pressure (t). That is, whereas Venturi (and all generic DP) meters produce a fluctuating pressure field along the entire meter body, traditionally only a single DP is measured between the inlet and the throat. DP Diagnostics has developed the principle that the **entire** pressure field holds significantly more information about the flow rate and meter performance than the single traditional DP measurement. The Venturi meter in Figure 1 has been given a third pressure tap (d) downstream of the diffuser. This addition to the traditional 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} or "PPL"). This therefore offers an increased understanding of the pressure field through out the meter body. This view is more detailed than the traditional single DP measurement view.

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: $m_t = EA_t \varepsilon C_d \sqrt{2\rho \Delta P_t}$, uncertainty ± x% --- (2)

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

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

Traditionally, there is a single Venturi meter flow rate calculation. It is shown here as equation 2. However, with the additional downstream pressure tap three flow equations can be produced. That is, the recovered DP and PPL can also be used to find the flow rate with an "expansion" flow equation (see equation 3) and a "PPL" flow equation (see equation 4) respectively. Note that m_t , m_r and m_{ppl} represents the traditional, expansion and PPL mass flow rate equation predictions of the actual mass flow rate (m) respectively. The symbol ρ represents the inlet 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 minimum (or "throat") cross sectional area through the meter respectively. ε is an expansion factor accounting for gas density fluctuation through the meter. (For liquids ε =1.) The terms C_d, K_r and K_{ppl} represent the discharge coefficient, the expansion coefficient and the PPL coefficient respectively. These are found by calibrating the meter and each can be set as constant values with set uncertainty ratings, or, may each be fitted to the Reynolds number, usually at a lower uncertainty rating. The Reynolds number is expressed as equation 5. Note that μ is the fluid viscosity and D is the inlet diameter. In the case, of a flow coefficient being fitted to the Reynolds number, as the Reynolds number (Re) is flow rate dependent, each of the three flow rate predictions must be independently obtained by an iterative method. A detailed derivation of these flow rate equations is given by Steven [1].

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

Every Venturi meter body is in effect three flow meters. With three flow rate equations predicting the same flow through the 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 Venturi meter is operating correctly, no two flow predictions would match *precisely*. However, a correctly operating meter should have no difference between any two flow equations greater than the sum of the two uncertainties. The calibration therefore produces three more values, i.e. the maximum allowable difference between any two flow rate equations, i.e. ϕ%, ξ% & υ% as shown in equation set 6a to 6c[1]. If the percentage difference between any two flow rate equations is less than the set uncertainty then no problem is found. If however, the percentage

[1] Uncertainty settings are the diagnostic systems sensitivity control. Operators can choose to use lower uncertainties than the defaults suggested in this paper in order to increase the diagnostic sensitivity. However, this comes with the greater risk of false warnings as the diagnostics become more sensitive. In practice, if an operator is comfortable with the diagnostic system operation and no false alarms are occurring, then the operator is free to therefore increase the diagnostic system sensitivity by reducing the stated diagnostic parameter uncertainties.

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

Traditional to Expansion Meter Comparison: $\lambda\ \% = \left\{ \left(\dot{m}_r - \dot{m}_t \right) \Big/ \dot{m}_t \right\} * 100\%$ -- (7b)

PPL to Expansion Meter Comparison: $\chi\ \% = \left\{ \left(\dot{m}_r - \dot{m}_{PPL} \right) \Big/ \dot{m}_{PPL} \right\} * 100\%$ -- (7c)

difference between any two flow rate equations is greater than the set uncertainty then a metering problem is indicated 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. However, it is possible to take a different diagnostic approach. The **P**ressure **L**oss **R**atio (or "PLR") is the ratio of the PPL to the traditional DP. Like the Venturi meter flow coefficients the PLR is a meter characteristic for all Venturi meters 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 also be set values. That is, all DP ratios available from the three DP pairs are constant values for any given DP meter geometry and Reynolds number and can be found by the *same* calibration that finds the three flow coefficients. Thus we also have:

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

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

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

Here then is another method of using the three DP's to check a Venturi meters health. Actual DP ratios found in service can be compared to the calibrated values. Let us denote the percentage difference between the actual PLR and the calibrated value as $\alpha\%$, the percentage difference between the actual PRR and the calibrated value as $\gamma\%$, and the percentage difference between the actual RPR and the calibrated value as $\eta\%$. These values are found by equations 8a to 8c.

$$\alpha\ \% = \{(PLR_{actual} - PLR_{calibration})/PLR_{calibration}\} * 100\% \quad \text{--- (8a)}$$

$$\gamma\ \% = \{(PRR_{actual} - PRR_{calibration})/PRR_{calibration}\} * 100\% \quad \text{--- (8b)}$$

$$\eta\ \% = \{(RPR_{actual} - RPR_{calibration})/RPR_{calibration}\} * 100\% \quad \text{--- (8c)}$$

The standard calibration of a Venturi 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 (±ψ %, ±λ , ±χ %). ***These fifteen Venturi meter parameters found by a standard calibration define the Venturi meters correct operating mode***. Any deviation from this mode beyond the acceptable uncertainty limits is an indicator that there is a meter malfunction and the traditional meter output is therefore not trustworthy. Table 1 shows the six possible situations that should signal a warning. Note that each of the six diagnostic checks has ***normalized data***, i.e. each meter diagnostic parameter output is divided by the set allowable difference for that parameter.

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

Table 1. The Venturi meter possible diagnostic results.

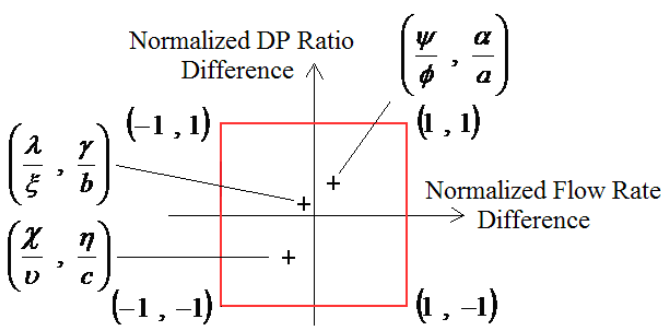


Fig 2. A normalized diagnostic calibration box with normalized diagnostic result.

For practical real time use, a graphical representation of the diagnostics continually updated on a control room screen can be simple and effective. Any such graphical representation of diagnostic results should be immediately accessible and understandable to the user. Therefore, it is proposed that three points be plotted on a normalized graph (as shown in Fig 2). This graphs abscissa is the normalized flow rate difference and the ordinate is the normalized DP ratio difference. 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 pair both the difference in the flow rate predictions and the difference in the actual to calibrated DP ratio are being compared to the set allowable differences (found by calibration). If all points are within the NDB the meter operator sees no metering problem. 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 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>Venturi Meter Standard and Diagnostic Calibration Issues</u>

This diagnostic system uses the discharge coefficient, the expansion flow coefficient, the PPL coefficient, PLR, PRR and the RPR. If the discharge coefficient and PLR are accurately known it is technically possible to derive the other four parameters from this information. Predictions for a Venturi meters PLR are given in the literature (e.g. Miller [2]). However, these are approximate values for approximate hydraulic loss calculations. These predictions are not intended for use in any precise diagnostic systems. Therefore, a Venturi meter must be calibrated to be made diagnostic ready. This is not a significant practical impediment to the application of the diagnostic system in the natural gas production industry as most Venturi meters in use in this industry are calibrated to find the classical discharge coefficient. The same calibration that finds this discharge coefficient can find the other diagnostic parameters at no extra expense.

Predictions for Venturi meter discharge coefficients over set flow condition ranges are given by ISO 5167 Part 4 [3]. However, it should be noted that ISO 5167 is <u>only</u> valid over set ranges of Venturi meter geometries and flow conditions. ISO 5167 discusses the high precision machined convergent section Venturi meter. This is the Venturi meter type primarily used for natural gas flow production. The limits of this meters ISO performance declaration are:

$$50 \text{ mm } (2") \le D \le 250 \text{ mm } (10")$$
$$0.4 \le \beta \le 0.75$$
$$2e5 \le \text{Inlet Reynolds Number } (D) \le 1e6$$

ISO 5167 states that if the Venturi meter is within the given geometry and flow condition range the discharge coefficient is a constant, i.e. $C_d = 0.995$ to an uncertainty of ±1%. However, if the geometry and flow condition range are outside this range then the discharge coefficient and uncertainty rating is unknown. ISO 5167 also states:

"Research into the use of Venturi tubes in high-pressure gas [$\ge$ 1 MPa ($\ge$ 10 bar)] is being carried out at present. In many cases for Venturi tubes with machined convergent sections discharge coefficients which lie outside the range predicted by this part of ISO 5167 by 2% or more have been found. <u>For optimum accuracy Venturi tubes for use in gas should be calibrated over the required flow rate range</u>."

ISO also state that a simultaneous use of the limits extreme values of D, β, Re(D) shall be avoided as otherwise the ISO set discharge coefficient value is likely to increase. ISO therefore states that for <u>installations outside these diameter, beta ratio, pressure and</u>

Reynolds number limits, it remains necessary to calibrate the meter in its actual conditions of service. Many industrial applications have pressures greater than 10 bar and Reynolds numbers greater than 1e6 and many applications have pipe diameters greater than 10”. **Therefore, in many actual applications the ISO Venturi meter standard is inapplicable.** In such cases the discharge coefficient must be found by calibration across the range of flow conditions for which the meter will be used. Therefore, for many industrial flow metering applications it is necessary to calibrate Venturi meters. Hence, it only takes the addition of an extra DP transmitter during the standard calibration set up to calibrate the meter for all diagnostics.

4. Industrial Applications of Venturi Meter Diagnostics

Swinton Technology developed the DP Diagnostics generic DP meter diagnostic system and produced an industrially ready system called “Prognosis”. In 2010 and 2011 Prognosis was added to the specifications of four Centrica Venturi meters and one Petronas Venturi meter. The four Centrica Venturi meters (comprising of three Solartron 6”, 0.4 beta ratio meters and one Solartron 10”, 0.4 beta ratio meter) were calibrated with dry natural gas flow at the GL Flow Centre in the UK. The DP Diagnostics manufactured Petronas 6”, 0.7 beta ratio Venturi meter was calibrated with dry natural gas flow and also tested with wet natural gas flow at the CEESI multiphase wet gas flow facility in the US. The results of each calibration / test and subsequent data analysis are now discussed.

4a. Centrica 6”, 0.4 Beta Ratio Venturi Meter Gas Calibrations at the GL Flow Centre

The three Solartron 6”, 0.4 beta ratio Venturi meters were nominally identical, i.e. they were built to the same drawing with the same material specification, by the same manufacturing facility. Therefore, all three meters were tested in the same calibration set up one after the other. The pressure of the natural gas calibration system was set at approximately 56 Bar(a).

Fig 3. Solartron 6”, 0.4 Beta Ratio Venturi meter (S/N 4103) at GL Flow Centre.

Figure 3 shows Venturi S/N 4103 installed at GL Flow Centre. The upstream and downstream straight pipe length requirements of ISO 5167 are met. Flow is from right to left. Note the three pressure taps. The first two are the traditional pressure ports. The third pressure tap downstream of the Venturi meter body is on the dedicated downstream spool supplied with the meter. Note that in this design two thermo-wells exist between the Venturi diffuser exit and the pressure tap at 6D downstream of the diffuser exit. However, as the meter is being calibrated with these thermo-wells in place their affects are fully accounted for. Figures 4, 5 & 6 shows the three 4", 0.4 beta ratio Venturi meter discharge coefficient, expansion coefficient and PPL coefficient calibration results respectively. Figures 7, 8 & 9 shows the three 4", 0.4 beta ratio Venturi meter PLR, PRR and RPR calibration results respectively.

All data plotted for the 6", 0.4 beta ratio Venturi meters between Figures 4 & 10 are for DP's > 20 mBar. Each meters flow coefficients are fitted to the Reynolds number by a

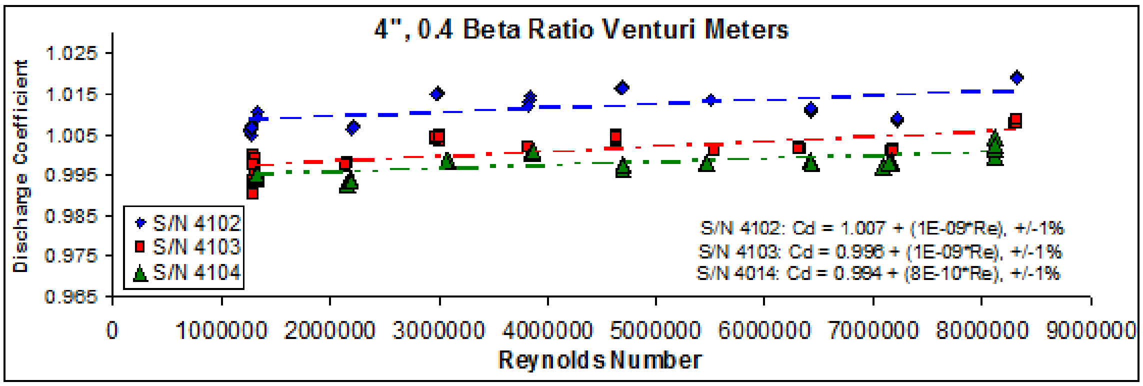


Fig 4. Three 4", 0.4 beta ratio Venturi meter discharge coefficient calibration results.

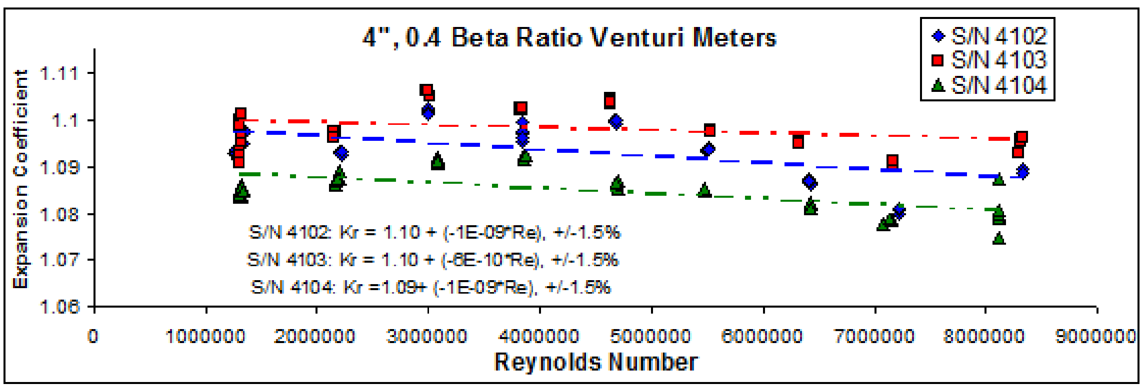


Fig 5. Three 4", 0.4 beta ratio Venturi meter expansion coefficient calibration results.

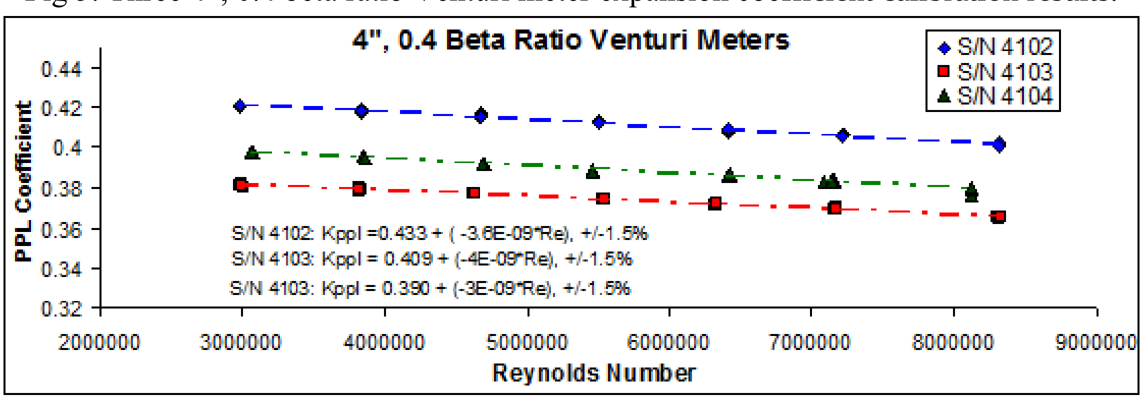


Fig 6. Three 4", 0.4 beta ratio Venturi meter PPL coefficient calibration results.

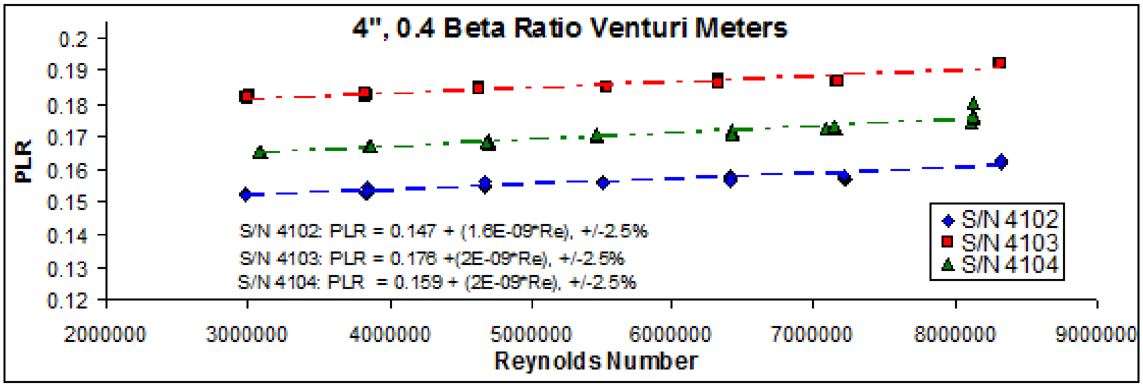


Fig 7. Three 4", 0.4 beta ratio Venturi meter PLR calibration results.

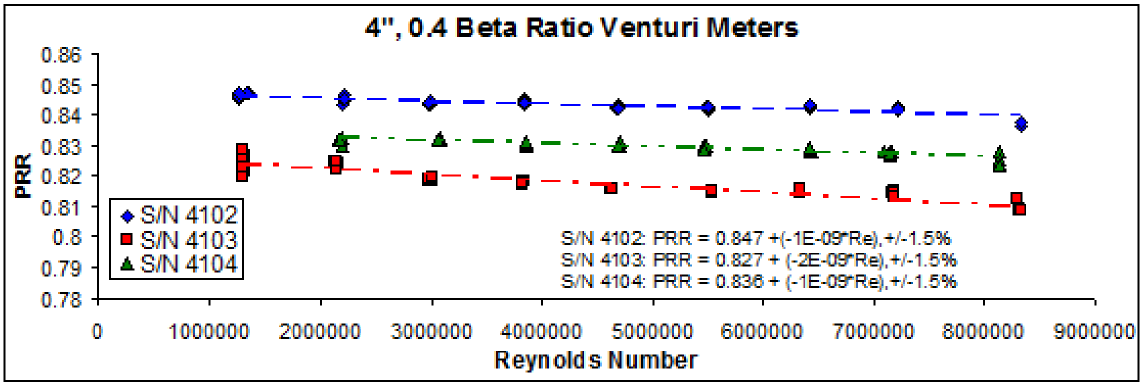


Fig 8. Three 4", 0.4 beta ratio Venturi meter PRR calibration results.

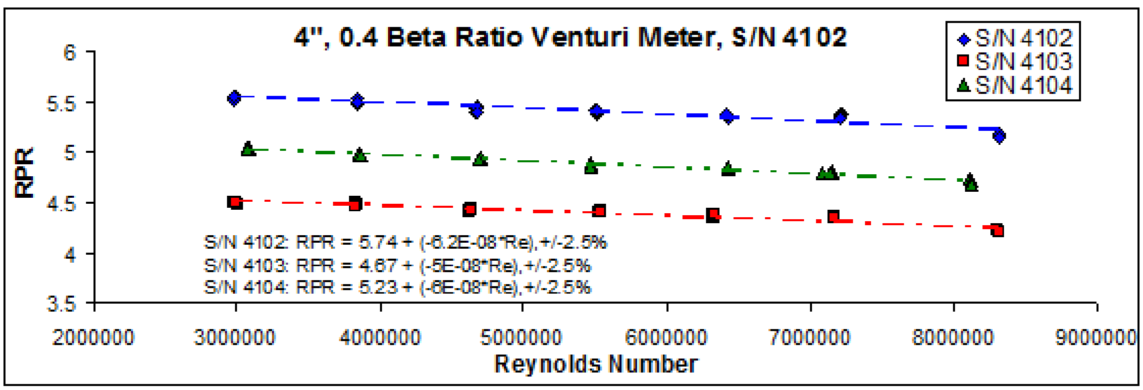


Fig 9. Three 4", 0.4 beta ratio Venturi meter RPR calibration results.

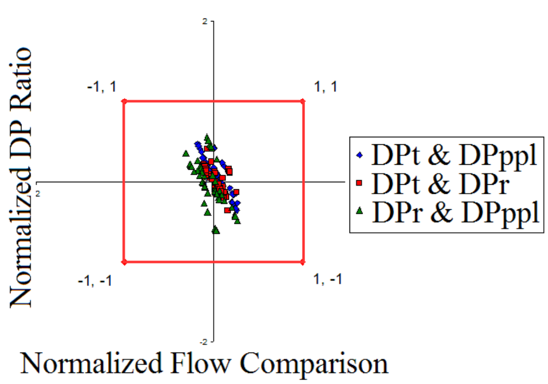


Fig 10. Baseline Calibration Data of S/N 4103 on a Normalized Diagnostic Box.

linear line. The discharge coefficients were fitted to ±1% uncertainty as expected. The expansion and PPL coefficients were both fitted to ±1.5% uncertainty. This shows that these unorthodox flow rate prediction methods are real and of practical use. These flow coefficient to Reynolds number fits mean that each of the three flow rate predictions (i.e. equations 2 thru 4) are predicted by iteration of the flow rate. With flow computers this iteration is straightforward meaning that there are three practical independent flow rate prediction methods available.

Each meters three DP ratios are related to the Reynolds number by a linear fit. The three meters PLR, PRR and RPR values were all fitted to ±2.5%, ±1.5% and ±2.5% uncertainties respectively. This shows that the three DP ratios are characteristics of the meter and useful for diagnostic purposes. Figure 10 shows the result of S/N 4103 meters calibration data fits being applied to its data set and the associated diagnostic results being plotted on the Normalized Diagnostic Box. (This meter was chosen randomly as an example, S/N's 4102 and 4104 had very similar NDB plots.)

However, the fact that the DP ratios are related to the Reynolds number is a potential impediment to the integrity of the diagnostic system. Unlike the three flow rate prediction methods, each DP ratio calculation can not produce an associated Reynolds number prediction. In order to find the correctly operating meters DP ratio "baseline" values the correct Reynolds number must be assigned from an external source to each of the meters three DP ratio vs. Reynolds number linear fits. However, there is a problem in this logic. In practice the only source available is the internal Reynolds number prediction from the meters flow rate outputs. The aim of the diagnostic method is to check that the traditional meter is operating correctly. However here, the traditional meter output (in the form of the Reynolds number prediction) is being used *with the assumption* it is correct to calculate the baseline DP ratios that will be used to investigate whether the traditional meter is correct! If the meter malfunctions it predicts the wrong flow rate and therefore the wrong Reynolds number. This wrong Reynolds number is subsequently used to predict the wrong baseline DP ratio values. Therefore, a malfunctioning meter can have **both** a changed actual DP ratio **and** an incorrect baseline value. This issue potentially undermines the integrity of the diagnostic system.

Fortunately, in practice this is not a significant problem. It can be seen in Figures 7 thru 9 that each of the three DP ratios are *relatively* insensitive to the Reynolds number. The DP ratio values change slowly over wide Reynolds number changes. It takes a large flow rate and Reynolds number prediction error to induce even a very small DP ratio baseline bias. For example, consider meter S/N 4102 and a Reynolds number of 5e6. The three DP ratio predictions at this Reynolds number are shown in Table 2. Let us now assume there is a meter malfunction and the meter has a flow rate error of +25%. However, it can be seen in Table 2 that even this relatively large Reynolds number bias produces DP ratio prediction biases that are less than the correctly operating meters DP ratios prediction

Parameter	Correct Re: 5e6	With +25% flow error	% Difference	Set Uncertainty %
Predicted PLR	0.155	0.157	+1.3%	±2.5%
Predicted PRR	0.842	0.841	-0.15%	±1.5%
Predicted RPR	5.431	5.35	-1.5%	±2.5%

Table 2. S/N 4102 Meter DP Ratio Prediction Shift with a +25% Flow Rate Error.

uncertainties. Of course, there are cases when a Venturi meter could have a malfunction significantly greater than ±25% (e.g. a large object partially blocking the Venturi throat or a heavy liquid loading wet gas flow). However, even when a meter malfunction is great enough to induce DP ratio baseline value shifts greater than the DP ratio baseline value uncertainty this malfunction also induces actual read DP ratios errors an order of magnitude greater again. That is, the actual DP ratio values are *far* more sensitive than the baseline predictions to an actual malfunctioning meter. Hence, even with a very significant meter malfunction the associated DP ratio baseline biases are not large enough to be of any practical significance relative to the actual DP ratio shifts. The diagnostic system still sees the significant difference between the actual and the slightly skewed DP ratio value baseline and therefore correctly identifies a malfunction has taken place. That is, in practice it doesn't matter that the DP ratio baseline has a small bias caused by a significant meter malfunction. Due to the actual DP ratio values relatively high sensitivity and the DP ratio baseline calculations relatively low sensitivity to meter malfunctions the DP ratio diagnostic checks still show a meter malfunction problem very clearly.

4a.1. <u>Inter-comparison of Three Nominally Identical Venturi Meter Calibration Results</u>

It is common for companies to buy multiple identical flow meters in one "batch" order. Nominally identical meters built to the same drawing, from the same material, by the same manufacturer in the same fabrication shop by the same staff using the same fabrication equipment may look truly identical to the casual observer. They may even look identical after inspection. However, they are seldom truly identical. Manufacturing tolerances make each meter unique. Hence, batch Venturi meters should be individually calibrated. Therefore, the three nominally identical 6", 0.4 beta ratio Venturi meters were each calibrated individually.

Most meters so calibrated have the resulting flow coefficient assigned to that meters serial number (S/N) for future implementation in the meters flow computer. Assigning the correct calibration information to each meter when a batch of "identical" meters have been individually calibrated is traditionally left to operator due diligence. If an error is made, and the wrong calibration is assigned to a meter, a bias will exist in its output that may not be noticed. For example, if two meters are nominally identical but their respective discharge coefficients are found by calibration to be off set by say 1%, then if the two discharge coefficients were mixed up, then one meter runs with a plus 1% bias and the other with a -1% bias. The reality of natural gas production dictates that conventionally there is no realistic way the operator would see this induced systematic bias. However, if Venturi meters are fully calibrated to be made diagnostic ready then the application of Prognosis will immediately and clearly indicate if such a human error has occurred. The three nominally identical Centrica 6", 0.4 beta ratio Venturi meter calibrations can be used to show this.

Table 3 shows the three Centrica 6", 0.4 beta ratio Venturi meter calibration results for the discharge coefficient at various Reynolds numbers. Two of the meters (S/N 4103 & S/N 4104) have very similar discharge coefficients. However, S/N 4102 has a discharge coefficient more than 1% higher than the other two meters discharge coefficients. This is a typical result when multiple nominally identical Venturi meters are calibrated and hence it is important to individually calibrate each Venturi meter. If either the calibration

Re	2e6	4e6	6e6	8e6
Calibrated Cd S/N 4102	1.009	1.011	1.013	1.015
Calibrated Cd S/N 4103	0.998	1.000	1.002	1.004
Calibrated Cd S/N 4104	0.996	0.997	0.999	1.000

Table 3. The 6", 0.4 beta ratio Venturi meter traditional calibration results.

Re	2e6	4e6	6e6	8e6
PLR S/N 4102	0.1502	0.1534	0.1566	0.1598
PLR S/N 4103	0.1796	0.1832	0.1868	0.1904
PLR S/N 4104	0.1630	0.1670	0.1710	0.1750

Table 4. The 6", 0.4 beta ratio Venturi meter PLR calibration results

data of meter S/N 4103 or meter S/N 4104 gets mixed up with the calibration of meter S/N 4102 a bias greater than 1% is created in the traditional flow rate calculation outputs. For example, if the meter with S/N 4104 received the calibration data fit of the S/N 4102 meter a positive bias greater than 1% would be induced on the S/N 4104 meters gas flow rate prediction. On the other hand if the meter with S/N 4102 received the calibration data fit of the S/N 4104 meter a negative bias greater than 1% would be induced on the S/N 4102 meters gas flow rate prediction. Traditionally there is no method available to indicate this other than due diligence.

Table 4 shows the same calibration results with respect to the PLR. Unlike the discharge coefficient there is a marked difference between all three flow meters PLR values. Such variance in nominally identical Venturi meter PLR values is typical, and this is why ISO 5167 Part 4 (2003) gives a loose prediction of the Venturi meters PLR being somewhere between 0.05 and 0.2 (i.e. a PLR between 5% & 20%). Clearly, Table 4 shows all three PLR's are indeed in this range. However, clearly there is a substantial difference in the PLR's between any two of the three meters.

The result of this PLR difference is that these diagnostic capable meters can not be mistaken for one another. In fact this is just a single diagnostic example (i.e. point y_1 in a NDB plot). Other diagnostic checks can also easily show this mistake. Figures 11a and 11b show examples of NDB plots when the calibration results from one meter was used

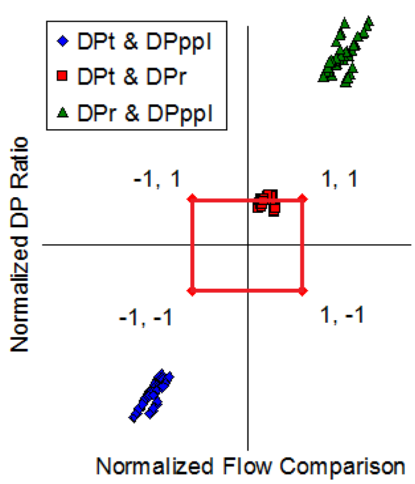


Fig 11a. S/N 4102 with S/N 4104 cal
Approx Flow Error: -1.5%

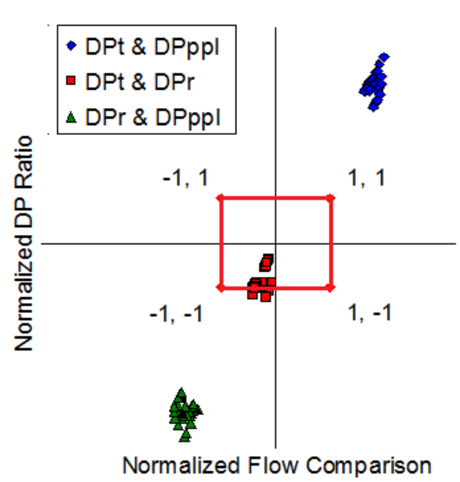


Fig 11b. S/N 4104 with S/N 4102 cal
Approx Flow Error: +1.5%

with another meter. Clearly the diagnostic system easily sees such a problem and therefore protects the end user against these potential flow rate prediction biases. This is understood to be the first system to guard against such human error using a simple, practical and effective technical check rather than relying on due diligence of all personnel involved in the calibration and commissioning of the flow meters.

4a.2. <u>One Ten Inch Venturi Meter Calibration (S/N 4101)</u>

The GL Flow Centre calibrated a Solartron 10", 0.4 beta ratio Venturi meters (S/N 4101). This meter was geometrically similar to the three 6", 0.4 beta ratio Venturi meters. Figure 12 shows the meter installed at the GL Flow Centre. The straight pipe length requirements of ISO 5167 are met. Flow is from right to left. Note the downstream tap downstream of the two thermo-wells. The calibration includes the effect of the thermo-wells in the diagnostic parameters. The pressure of the natural gas calibration system was set at approximately 56 Bar(a). Figures 13 and 14 show the full diagnostic system calibration results for Venturi meter S/N 4101. Figure 15 shows the result of S/N 4101 meters calibration data fits being applied to its data set and the associated diagnostic results being plotted on the Normalized Diagnostic Box. As with the 6", 0.4 beta ratio Venturi meters the minimum DP value used by the diagnostics was set at 2000 Pa / 20 mBar / 8"WC.

Fig 12. Solartron 10", 0.4 Beta Ratio Venturi meter (S/N 4101) at GL Flow Centre

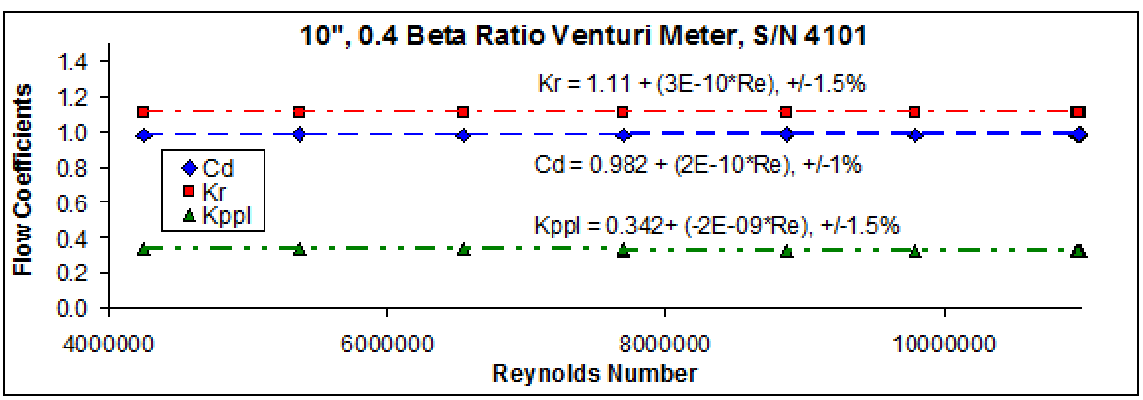


Fig 13. 10", 0.4 beta ratio Venturi meter (S/N 4101) flow coefficient calibration results.

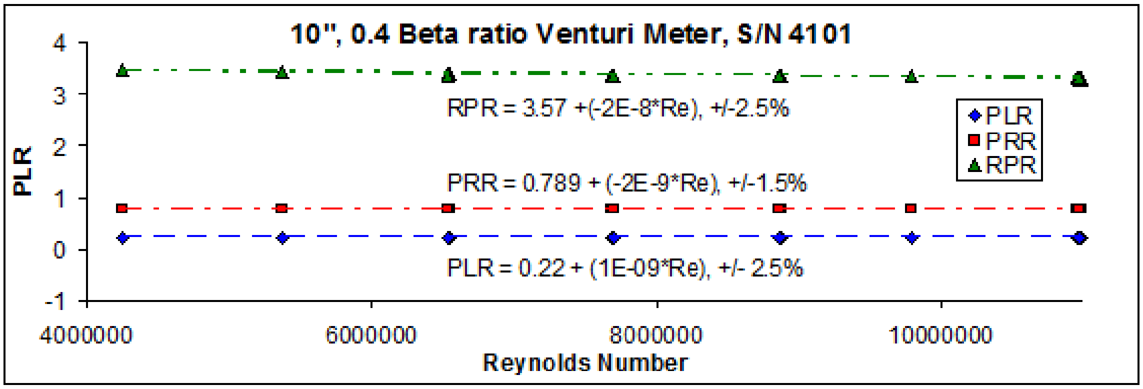


Fig 14. 10", 0.4 beta ratio Venturi meter (S/N 4101) DP ratio calibration results.

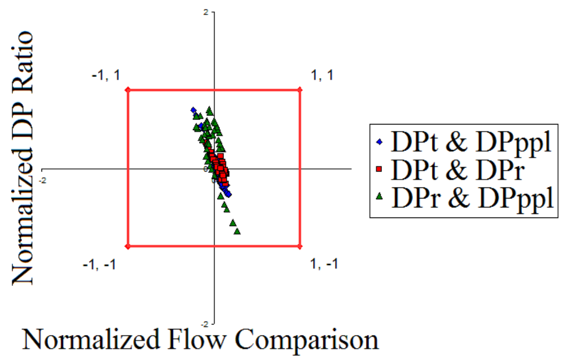


Fig 15. Baseline Calibration Data of S/N 4101 on a Normalised Diagnostic Box.

4b. Worked Examples of Diagnostic Warnings for Various Hypothetical Malfunctions

The 10" Venturi meter will now be used to give examples of the diagnostics indicating meter malfunctions. With no deliberate flow meter malfunctions being tested at the GL Flow Centre there are no real data sets to analyze regarding a malfunctioning meter. However, there are several virtual scenarios that can show the diagnostics operating. Such examples are incorrectly keypad entering the inlet diameter (high and low), incorrectly keypad entering throat diameter (high and low), a saturated traditional DP transmitter and a blocked impulse line at the throat. Note that in the first two examples the DP's read are unaffected and hence there is no difference in the NDB plot for the case of reading all three DP's directly and the case of only reading the traditional DP & PPL and inferring the recovered DP. However, in the third and fourth example the DP measurements are affected. When DP measurement is affected by a system malfunction the diagnostics will show a warning regardless of whether the three DP's are individually read or whether only two DP's are read and the third inferred. However, the different ways of obtaining the three DP's produces a different diagnostic pattern. Naturally, there is more information obtainable from the case of the three DP's read independently. Therefore, the third and fourth examples will show separately the results for these two DP reading possibilities.

Example 1. Keypad Entry Error of Inlet Diameter Too High & Too Low

The nominal 10" schedule 120 meter has a listed inlet diameter of 9.062" / 230.175 mm. The actual meter was measured at 9.0591" / 230.1mm. A nominal 10" schedule 100 meter has a listed inlet diameter of 9.312” / 236.525 mm. If, in way of an example, we input the diameter for a nominal schedule 100 meter, the meter inlet diameter is entered as larger than it actually is. This causes a flow rate prediction negative bias. In fact, the Venturi meter is very insensitive to such diameter errors. This incorrect diameter error of +2.8% corresponds to a negative flow rate bias less than 0.5%. However, the diagnostics are very sensitive to the issue. Figure 16a shows the result. Note that for Venturi meter S/N 4101 the correct diameter gave the diagnostic result shown in Figure 15.

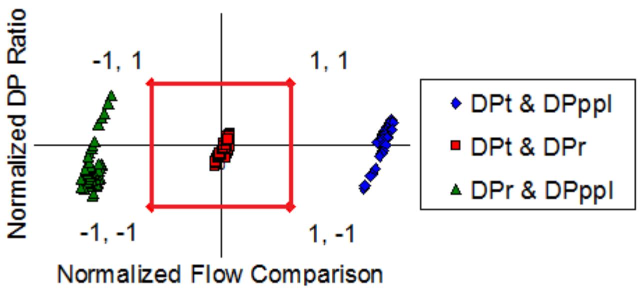


Fig 16a. Inlet Diameter Entered Too High

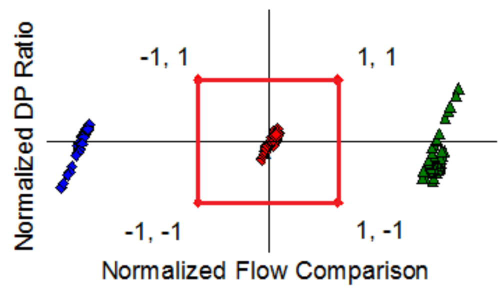


Fig 16b. Inlet Diameter Entered Too Low

The nominal 10” schedule 140 meter has a listed inlet diameter of 8.75” / 222.5 mm. If we input the diameter for a nominal schedule 140 meter the meter inlet is entered as smaller than it actually is. This causes a positive flow rate prediction bias. As the Venturi meter is very insensitive to diameter errors this incorrect diameter error of -3.4% corresponds to a positive bias less than 0.5%. However, the diagnostics are very sensitive to the issue. Figure 16b shows the result.

Prognosis can see keypad entered inlet diameter errors even when the associated bias in the flow rate prediction is extremely small, and well inside the meters stated flow rate prediction uncertainty. In fact, the diagnostic system appears to be most sensitive to this measurement error issue when compared to all other issues tested so far. However, the opposite is true of the throat diameter keypad entry error.

Example 2. <u>Keypad Entry Error of Throat Diameter Too High & Too Low</u>

The 10” schedule 120 meter (S/N 4101) has a listed throat diameter of 92.03 mm. If we keypad enter the throat diameter incorrectly, say by entering too small a throat diameter by swapping two digits, so as the computer received 90.23mm we induce a flow rate prediction negative bias. The Venturi meter is very sensitive to throat diameter errors (as the erroneous value is squared in the flow rate equations throat area term – see equation 2). This -2% throat diameter error produces approximately a -4% flow rate prediction error. Figure 17a shows the corresponding diagnostic result. If we give the throat diameter keypad entry a positive error by entering say 94.03mm (instead of 92.03mm) then this +2% throat diameter error produces a +4% flow rate prediction error. Figure 17b shows the corresponding diagnostic result. The diagnostics are *relatively* insensitive to this issue. Note that for the Venturi meter S/N 4101 the correct diameter gave the diagnostic result shown in Figure 15.

Prognosis can see keypad entered throat diameter errors if the throat diameter error is greater than approximately 1.5%. Whereas this corresponds to a diagnostic warning that

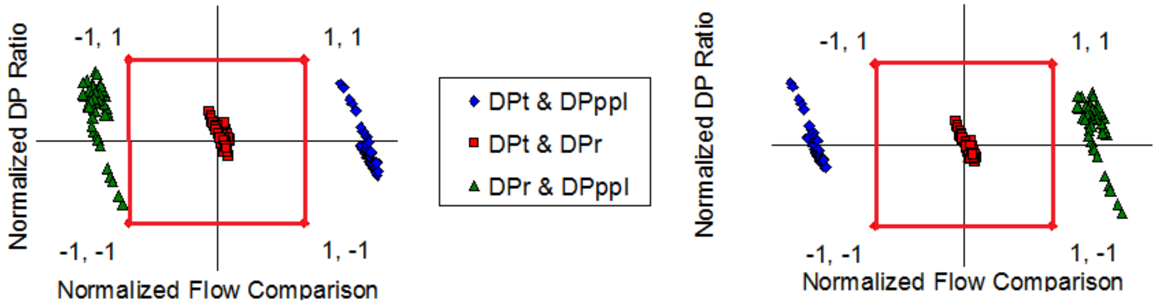


Fig 17a. Throat Diameter Entered Too Low Fig 17b. Inlet Diameter Entered Too High

appears when flow is incorrectly predicted by approximately 2.5% or more, this should be taken in context. This is by far the most difficult issue to diagnose of all the Venturi meter malfunctions investigated (including those outside the scope of this paper) and the diagnostic system can still see when the throat has been incorrectly inputted at 1.5% error or more. Currently industry has no alternative diagnostic system of *any* specifications.

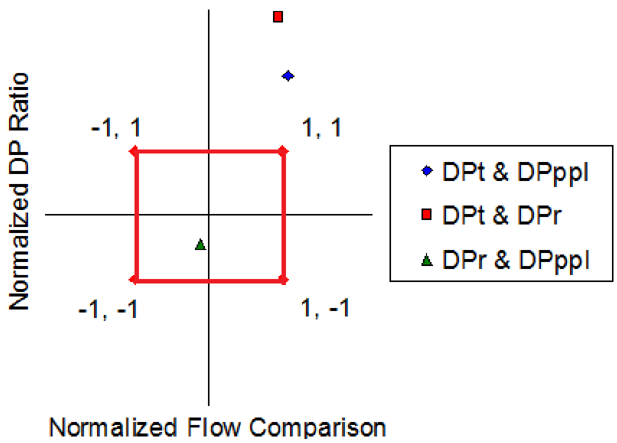
<u>Example 3. A Saturated DP Transmitter</u>

Venturi meters are dependent on their instrumentation being serviceable. Therefore, a common problem is the actual traditional DP being produced being a higher value than the maximum value the DP transmitter can measure. In such a situation the DP transmitter is said to be "saturated". A saturated DP transmitter does not normally have any warning associated with it. If a DP transmitter becomes saturated it continues to send a DP value to the flow computer but this value is the DP transmitters upper DP limit, not the correct higher DP value. Hence, a saturated DP transmitter causes a DP meter to under-read the actual flow rate. Examples are now given showing the diagnostics response to this scenario.

Unlike the earlier examples where the DP's were being correctly read the saturated DP transmitter example has different diagnostic results depending on whether three DP's are being individually read or whether two DP's are being read and the third inferred. Therefore, in this example we will consider both scenarios. Let us consider the GL Flow Centre's calibration data for meter S/N 4101. Any flow point can be used so a single randomly selected data point is chosen as an example. During one calibration point the actual traditional DP was recorded correctly as 419.95 mBar. However, let us imagine that the DP transmitter was spanned to read 400 mBar at 20mA. If this was the case then the transmitter would have read 400 mBar[2] when the actual DP was 419.95 mBar. In such a scenario the traditional flow rate prediction error would have been -2.4%.

If all three DP's were individually read (and we assume in this particular example that only the traditional DP transmitter is saturated) then only the traditional DP value is incorrect. However, if only two DP's are read (i.e. the traditional DP and the PPL) and the third (i.e. the recovered DP) is inferred, then the saturation of the traditional DP transmitter means that both the traditional and recovered DP's will be erroneous. These two scenarios have different affects on the diagnostic system.

[2] In reality DP transmitters do not usually saturate precisely at the upper range limit but somewhat above it. However, stating a saturation value of 400 mBar here is suitable for the sake of example.



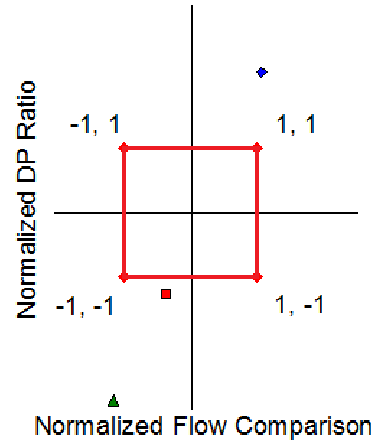


Fig 18a. Saturated DP_t, all 3 DP's read
Fig 18b. Saturated DP_t, 2 DP's read

Figure 18a shows the result if all three DP's are individually read. Prognosis correctly shows a warning of a malfunction. However, the pattern on the NDB gives more information. Note that both the traditional DP & PPL pair and the traditional & recovered DP pair have both moved outside the NDB into the first quadrant, i.e. both the PLR and PRR have both become larger than their calibrated baseline values. However, as equation 1a is a consequence of the first law of thermodynamics, it can not be violated. As a consequence, any *physical* problem with the meter body that causes the PLR to shift in one direction from the correct operating value must also cause the PRR to shift in the *opposite* direction. That is, no physical problem with the meter body can cause DP's to behave in the way shown in Figure 18a. Hence, such a pattern dictates that not only is there a meter malfunction, but as the physical world can not produce this pattern the problem lies with one or more incorrectly read DP's. It can then be seen that when comparing the recovered DP and PPL they show no problem. The two points showing a problem have one common DP, the traditional DP. Hence, Prognosis has shown there is a problem, it is a problem with the DP readings, and in particular it is a problem with the traditional DP reading. Once, it is established that the recovered DP and PPL are correct then the flow rate predictions from the expansion meter and PPL meter can be trusted. Or, as it is known that the recovered DP and PPL are correct, equation 1 will give the actual traditional DP for use with the traditional flow equation. Furthermore, by comparing the correct flow rate prediction to the erroneous flow rate prediction Prognosis can even indicate the size of the flow rate error due to the identified saturated DP transmitter. That is, in this example there is a saturated traditional DP (400 mBar) and a correctly read recovered DP (325 mBar) and a correctly read PPL (95 mBar). However, equation 1 states that the sum of the recovered DP and PPL must be the traditional DP (i.e. 420 mBar). Hence, a simple Prognosis diagnostic is to show that equation 1 is not holding:

$$DP_{t,\,read} \neq DP_{r,\,read} + DP_{PPL,\,read} = DP_{t,\,inferred}$$

Figure 18b shows the scenario if the traditional DP and PPL are read and the recovered DP is inferred. In this case it is inherently assumed that the equation 1 must hold and hence the inferred recovered DP is also erroneous. As the traditional DP is read erroneously at 400 mBar and the PPL is correctly read at 95 mBar, it is assumed that the recovered DP is 305 mBar. That is, unlike the situation with three DP's being individually read, equation 1 can not see any problem if the system only uses two DP transmitters and infers the third DP value. However, when the erroneous traditional and recovered DP's and the correct PPL value are then used in the diagnostic calculations Figure 18b shows the result. Prognosis indicates that the meter has malfunctioned. However, the pattern is different to when the three DP's are individually measured. The pattern in Figure 18b does not suggest that the first law of thermodynamics has been violated (because we falsely inferred the recovered DP by applying equation 1 in the *assumption* that the measured DP's were correct). Therefore, when only using two DP transmitters the diagnostics do show a malfunction but the malfunction is unspecified. In this case it is not possible to indicate that it is a DP transmitter problem, and nor is it possible to indicate which transmitter has the problem. However, even with two DP readings only, compared to traditional Venturi meters without diagnostics, the fact that there is a reliable warning of an unspecified problem is a very significant improvement. Nevertheless, Prognosis is far more powerful when the three DP's are individually read.

Example 4. Blocked Impulse Line Induced DP Reading Errors

The blocking of impulse lines is a concern. Impulse lines are the tubing connecting the DP transmitters with the meter body. They can be blocked by contamination, hydrates, scale, salts, etc., or by a user forgetting to open a valve on the DP transmitters manifold. A blocked impulse line scenario is different to a single DP transmitter having a problem such as being saturated, or drifting, or incorrectly spanned. In these scenarios the single DP transmitter gives an incorrect DP reading. However, for any one of the three pressure ports and associated impulse lines, two of the three DP measurements will require the pressure difference between that port and another port to be measured. If the fluid in an impulse line is trapped due to a blockage at a pressure different to that being produced by the flow, then two DP readings are going to be incorrect even if the DP transmitters themselves are fully serviceable. In this scenario the DP's read are the same regardless of whether two or three DP transmitters are utilized to find the three required DP's. That is, for the case of a blocked impulse line, an inferred or directly read third DP value gives the same three measured DP's with two of these DP's being in error. Hence, the following example holds for either way of finding the three DP's.

A random S/N 4101 calibration point is taken. Naturally, the GL Flow Centre read the correct DP's. However, as an example, DP Diagnostics have applied a +4% and then a -4% shift in the traditional DP read to simulate a blockage in the throat pressure tapping impulse line. That is, the throat pressure is simulated as blocked at a lower pressure and then a higher pressure than true. This also causes an error to appear in the recovered DP value (of +5% and then -5% respectively) but no error to occur in the measured PPL. (Note that this statement is true regardless of whether two or three DP transmitters are used.) The corresponding error induced on the traditional Venturi meters flow rate prediction is approximately +2% and -2% respectively. Traditionally there is no warning system internal to the Venturi meter system to indicate any such problem exists.

Figures 19a and 19b show the diagnostic systems response to the two examples of a throat port blocked at a lower pressure and higher pressure respectively. The diagnostic system is sensitive to this problem to approximately 1% flow rate error. However, unlike the scenarios of a single DP transmitter malfunctions, in the case of a blocked impulse

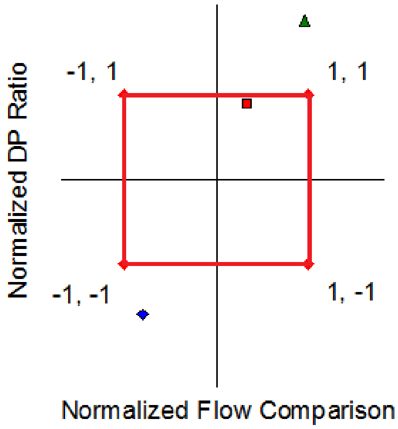
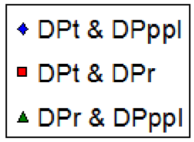


Fig 19a. Blocked Throat, Pressure Low



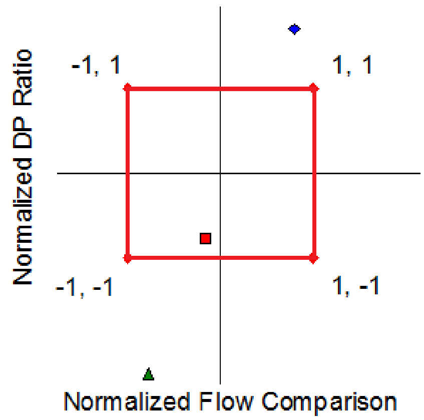


Fig 19b. Blocked Throat, Pressure High

line the diagnostic system can not confirm the source of the problem, but crucially it *does* show that a problem exists which is a very significant advance on the current situation of DP meters having no warning system whatsoever.

5. Wet Gas Flow Considerations

The GL Flow Centre calibrated the Centrica Venturi meters with dry natural gas flows only. It has been stated that there is potential for these meters to encounter wet gas flow in service. Although there is no wet gas flow data for the four Centrica Venturi meters it is possible to discuss the diagnostic systems response to wet gas flow by introducing another Venturi meter data set here.

Figure 20 shows a Petronas owned DP Diagnostics manufactured ISO compliant 6", 0.7 beta ratio Venturi meter under test at the CEESI wet natural gas facility. This meter was first calibrated at CEESI with air and then dry natural gas flow. Figure 21 shows the full calibration results. This meters particular industrial application with a wet natural gas flow meant that it did not require the precision of flow coefficient fits to Reynolds number. Therefore, in this particular case it was deemed unnecessary to use anything

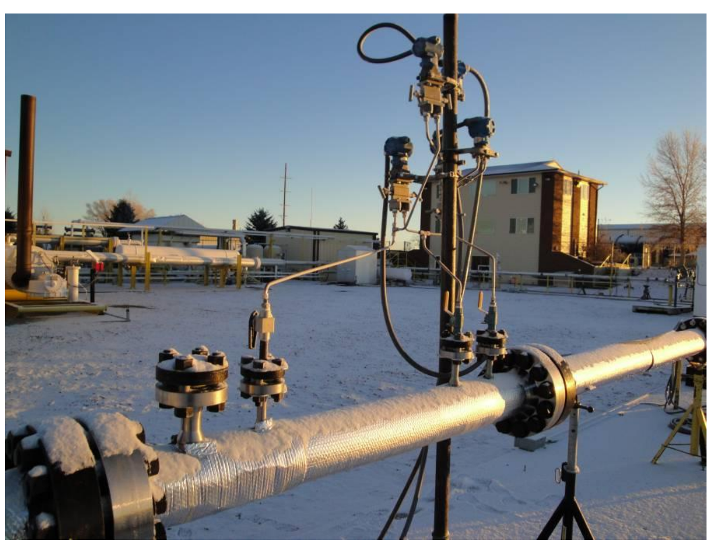
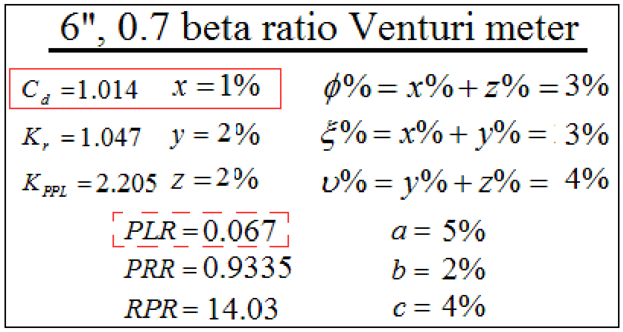


Fig 20. DP Diagnostics 6", 0.7 beta ratio Venturi meter at CEESI wet gas flow facility.



6", 0.7 beta ratio Venturi meter

$C_d = 1.014$	$x = 1\%$	$\phi\% = x\% + z\% = 3\%$
$K_r = 1.047$	$y = 2\%$	$\xi\% = x\% + y\% = 3\%$
$K_{PPL} = 2.205$	$z = 2\%$	$\upsilon\% = y\% + z\% = 4\%$
$PLR = 0.067$		$a = 5\%$
$PRR = 0.9335$		$b = 2\%$
$RPR = 14.03$		$c = 4\%$

Fig 21. DP Diagnostics Venturi meter calibration result summary.

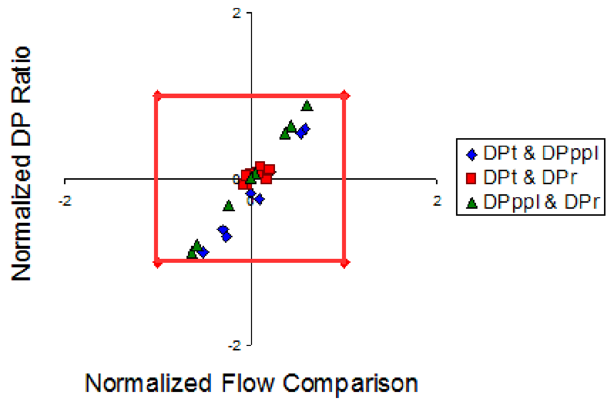


Fig 22. The Baseline Calibration data diagnostics result.

more complex than simple constant values for the six diagnostic parameters. Figure 22 shows this dry gas flow baseline data plotted on a Prognosis NDB. The wet gas flow data set recorded from this Petronas Venturi meter is now used to discuss the use of Prognosis specifically with respect to wet gas flow applications.

5a. Wet Gas Parameter Definitions

In order to describe wet gas flow conditions and the diagnostic systems response to them it is necessary to use several wet gas flow parameters. The required wet gas flow parameters are now defined.

$$X_{LM} = \frac{m_l}{m_g}\sqrt{\frac{\rho_g}{\rho_\ell}} \quad \text{--- (9)} \qquad\qquad DR = \rho_g / \rho_\ell \quad \text{--- (10)}$$

$$Fr_g = \frac{U_{sg}}{\sqrt{gD}}\sqrt{\frac{\rho_g}{\rho_\ell - \rho_g}} \quad \text{--- (11)} \qquad\qquad U_{sg} = \frac{m_g}{\rho_g A} \quad \text{--- (12)}$$

The Lockhart-Martinelli parameter (X_{LM}) is a non-dimensional parameter that describes the relative amount of liquid in a given wet gas flow. That is, it is a measure of the liquid loading of a wet gas flow. It is calculated by equation 9. Venturi meters have a wet gas flow response that is dependent on the pressure. The gas to liquid density ratio (DR) is a non-dimensional method of describing the line pressure. It is calculated by equation 10. Note that where 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. Venturi meters have a wet gas flow response that is dependent on the gas velocity. The gas densiometric Froude number (equation 11) is a non-dimensional way of describing gas velocity for a set pipe size and set fluid densities. In this equation, g is the gravitational constant, D is the pipe internal diameter and U_{sg} is the superficial gas velocity calculated by equation 12. Note that A is the meter inlet area.

5b. Venturi Meter Wet Gas Flow Diagnostic Capability Examples

Liquid in a flow predominately of gas induces a positive bias (or "over-reading") on a Venturi meters gas flow prediction. Figure 23 shows sample data of percentage over-reading to Lockhart-Martinelli parameter for a set gas to liquid density ratio and gas densiometric Froude number. This over-reading is reproducible and therefore wet gas flow correction factors exist that can correct for the liquid induced bias, as long as the liquid flow rate is known. For stand alone Venturi meters this liquid flow rate information must come from an external source. An issue with this is the fact that usually the liquid flow rate is found by tracer dilution or test separator spot checks and not from a continuous live reading. Hence, if the liquid flow rate changes between spot checks then the Venturi meter wet gas correlation will have an incorrect liquid flow rate input. This causes an error in the resulting gas flow rate prediction. It is therefore beneficial if the Venturi meter system itself can monitor the relative amount of liquid loading in the wet gas flow and warn the user if the liquid loading has changed.

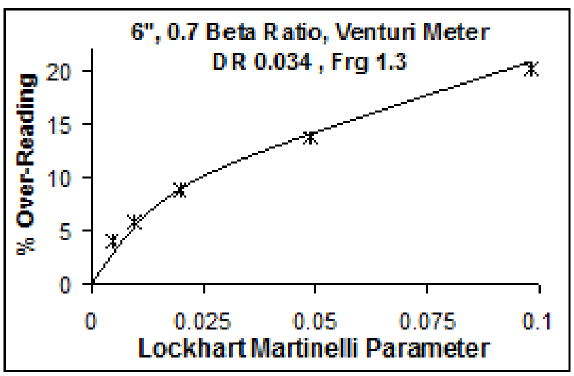


Fig 23. Sample Venturi over-reading data.

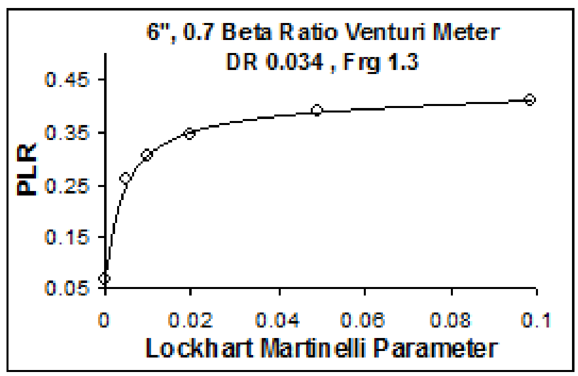


Fig 24. Sample Venturi PLR vs. X_{LM} data.

One popular method for monitoring the liquid loading of a wet gas flow through a Venturi meter is to monitor the PLR. The PLR of a Venturi meter with dry gas flow is a set meter characteristic for a given Reynolds number. However, a wet gas flow will cause the Venturi meters PLR to be higher than this dry gas value. As the wet gas flows liquid loading increases the PLR increases. Figure 24 shows sample data of PLR to Lockhart Martinelli parameter data for a set gas to liquid density ratio and gas densiometric Froude number. Hence, it is common for wet gas flow Venturi meters to include a PLR monitoring device as a *rudimentary* liquid loading monitor. However, such simple PLR monitors relate any shift of PLR with a change in liquid loading. Unfortunately, as we have seen in earlier examples, a changing wet gas flow liquid loading is not the only issue that can cause a PLR value to change. DP reading problems such as a saturated DP transmitter, or a blocked impulse line, or a drifting DP transmitter, etc. can all cause the PLR to appear to change even if the liquid loading remains constant. In such cases the existing systems may falsely indicate a change in liquid loading. Furthermore, like single phase Venturi meters, standard wet gas flow Venturi meters tend to not have any comprehensive diagnostics to monitor the health of the DP transmitters.

These new diagnostics allow easy monitoring of the PLR (and other diagnostic) parameters relative to the dry gas baseline, or if preferred, relative to any arbitrary set wet gas flow condition. Hence, when running a Venturi meter with the diagnostics in a wet gas flow application it is easy for a control room screen to show immediately when an event has occurred. Such an event could be a change in the liquid loading of a wet gas flow, **or** it could be an incorrect DP reading. However, while most wet gas flow Venturi meter systems automatically interpret any change in the PLR as a change in liquid loading, if Prognosis has the three DP's read individually it can distinguish between some DP measurement errors and a wet gas flow condition change. This is particularly useful for wet gas flow applications as wet gas flow can cause multiple problems for DP transmitters. The associated higher DP's caused by wet gas flow can cause transmitter saturation. Unsteady wet gas flow can cause significant and continuous DP fluctuations therefore inducing premature drift on the DP transmitter. Wet gas flow can also cause severe slugging that creates sudden sharp spikes of DP as the liquid slugs periodically passes through the Venturi meter. This phenomenon further increases the likelihood of DP transmitter premature drift. Therefore, a system that can monitor DP transmitter health in wet gas flow service and distinguish between a PLR shift due to liquid loading changes and DP reading problems can be very useful.

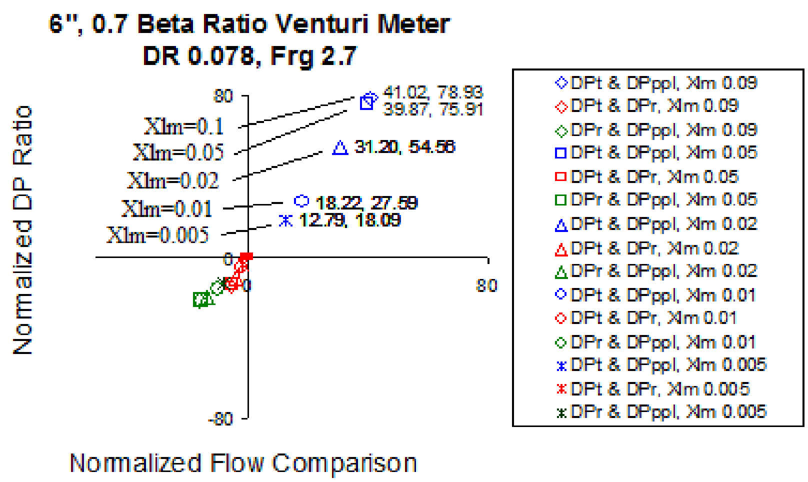


Fig 25. All data from density ratio 0.078, gas densiometric Froude number 2.7.

Figure 25 shows the DP Diagnostics 6", 0.7 beta ratio Venturi meter wet gas flow data for 75 Bar(a) / DR 0.078 and a gas densiometric Froud number of 2.7 on a NDB plot. A range of Lockhart Martinelli parameters are shown. The NDB plot shows these five wet gas flow conditions, each producing the three diagnostic points. It is clear that liquid loading affects the position of the points. The Venturi meter is very sensitive to wet gas flow. It takes very small amounts of liquid in a gas stream for a Venturi meters NDB plot to register a significant issue. The wet gas flow pattern on a NDB plot is always (for the points outside the NDB) the traditional DP and the PPL pair in the first quadrant with the other two DP pairs together in the third quadrant. This pattern does not automatically indicate a wet gas flow, it is possible other issues can cause such a pattern, but it is this pattern that wet gas will always produce. If this pattern does not exist, then wet gas is not flowing through the Venturi meter, or at least wet gas flow is not the only issue with the meter. A Venturi meters most sensitive DP pair to wet gas flow is the traditional DP and PPL pair. For each of the five wet gas flow condition NDB plots here it can be seen that this point is the furthest of the three points from the origin. However, as the Lockhart Martinelli parameter increases or reduces this point trends away or towards the NDB respectively at a faster rate than the other two associated points. Therefore, monitoring this traditional DP and the PPL point on the computer screen as it is updated with live DP data offers a real time check on the liquid loading of the wet gas flow.

The Venturi meter diagnostic system is so sensitive to wet gas flow that even at very low Lockhart Martinelli parameters the points are so far from the NDB that the NDB is a small box or dot at the centre of the plot (e.g. see Figure 25). Therefore, in this scenario the NDB is playing no useful part on the graphical display. In this case monitoring wet gas flow would facilitate the requirement for the user to memorize and monitor the point co-ordinates. However, there is an alternative. It is possible to "zero" the wet gas data plot, i.e. apply a correction factor for a given wet gas flow condition. The zeroing technique removes the effect of a **particular** wet gas flow condition thereby placing the points in the NDB. Then, if there is a subsequent change in liquid loading after this zeroing the points move back outside the NDB thereby indicating a change in liquid loading without the requirement for the operator to closely monitor the co-ordinates. The pattern of the points as they move outside the NDB indicates if the liquid loading has increased or reduced.

The zeroing factor is denoted as "Z". The definition of "Z" is the difference between the actual read pressure loss ratio (PLR_{act}) and the dry gas calibrated PLR value (PLR_{cal}), as shown by equation 13. Note by definition the range of Z is bound by -1 < Z < +1.

$$Z = PLR_{act} - PLR_{cal} \quad \text{--- (13)}$$

$$PLR_{act} = PLR_{cal} + Z \quad \text{-- (14)} \qquad PRR_{act} = PRR_{cal} - Z \quad \text{-- (15)} \qquad RPR_{act} = \frac{PRR_{act}}{PLR_{act}} \quad \text{-- (16)}$$

$$K_{r,\mathrm{mod}} = K_r \sqrt{1 + \frac{Z}{PRR_{act}}} \quad \text{-- (17)} \qquad K_{PPl,\ \mathrm{mod}} = K_{PPL} \sqrt{1 - \frac{Z}{PLR_{act}}} \quad \text{-- (18)}$$

The zeroing mechanism is to add the zeroing factor to the calibrated PLR (equation 14), subtract the zeroing factor from the calibrated PRR (equation 15) and to calculate the zeroed RPR from the ratio of the two zeroed PLR & PRR values (equation 16). The discharge coefficient is unchanged (by definition) but the expansion and PPL coefficients (K_r & K_{PPl}) are modified (as denoted by $K_{r,\mathrm{mod}}$ & $K_{PPl,\ \mathrm{mod}}$ respectively) as shown in equations 17 & 18.

An example of zeroing a wet gas point is given in Figure 26. Here a wet gas flow result for a gas to liquid density ratio of 0.078, a gas densiometric Froude number of 2.7 and a Lockhart Martinelli parameter of 0.005 is shown. The solid points are the standard points (with no zeroing) plotted on the NDB graph. In service the actual PLR and the calibrated PLR can be compared to find the correction factor, Z (see equation 13). In this example the zeroing factor is Z = +0.0606. This reduces all three points to within the NDB as

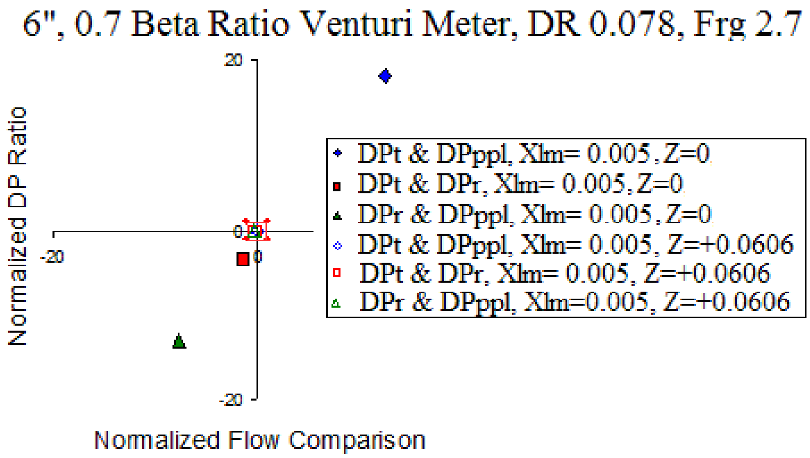


Fig 26. An example of a wet gas flow diagnostic plot before and after zeroing.

required (see the hollow points crammed into the NDB in Figure 26). Note, that Z = +0.0606 is stating that the liquids presence has increased the permanent pressure loss in absolute terms from the dry gas flow calibrated value of 6.7% of the traditional DP to 12.76% of the traditional DP:

$$PLR_{act} = PLR_{cal} + Z = 0.067 + 0.0606 = 0.1276, \text{ or } 12.76\%.$$

By applying the zeroing factor the wet gas flow condition performance is set in the system as the "normal" flow condition and the diagnostics points are retained inside the NDB .

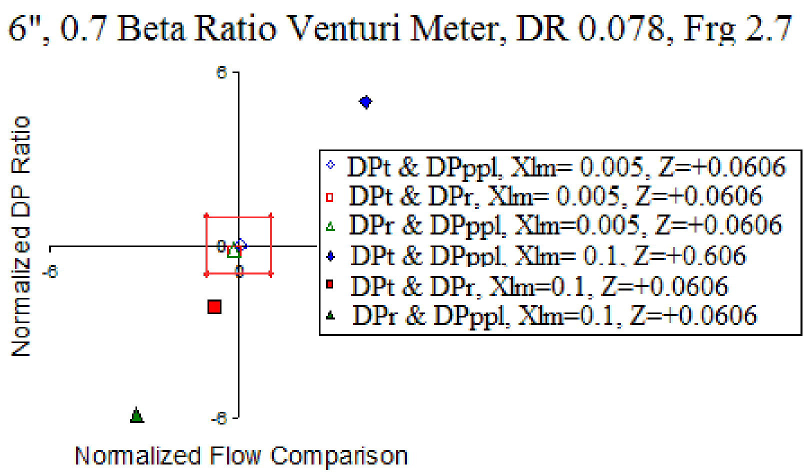


Fig 27. Example of meter zeroed to a wet gas condition with a change to that condition.

Now let us to consider what happens when running with that zeroing factor and the liquid loading changes. Figure 26 shows points zeroed to Z=+0.0606 and the system is set to show that wet gas flow as the normal flow condition. Figure 27 shows the result if this zeroing factor stays constant and the Lockhart Martinelli parameter increases. For all other wet gas flow parameters remaining constant the Lockhart Martinelli parameter was raised from 0.005 to 0.01. Without a change in the set zeroing factor the shift in the Lockhart Martinelli parameter has a dramatic effect on the diagnostic plot. The NDB plot has again a pattern suggesting a wet gas flow. (If the liquid loading reduced the pattern would have been the mirror image, i.e. the traditional DP & PPL point in the third quadrant and the other two points in the first quadrant, thereby indicating a reducing liquid loading.) Hence, the diagnostics would give an immediate and clear indication of a Lockhart Martinelli parameter change. Such an occurrence would indicate a new spot check of the Lockhart Martinelli parameter was required. In such a case, once the change in liquid loading is registered it is possible to re-zero the system to that new wet gas flow condition. In this case the new zeroing factor happens to be Z = +0.0924 (not shown).

This monitoring of the PLR for changes in liquid loading is fundamentally similar to the existing wet gas flow Venturi meter systems and only offers a possible advantage in the method of presentation. However, the diagnostics really come into their own when the meter does not just have wet gas flow but a secondary problem, such as the common wet gas flow problem of a DP transmitter malfunction. Let us consider a saturated DP transmitter. This gives the flow computer an artificially low DP value. Traditionally, there is no warning system to indicate to the operator that the system has a saturated DP transmitter and is therefore in error.

Some Venturi wet gas flow metering systems use the PLR reading instead of an external liquid flow rate input as part of the gas flow rate calculation. These systems do not typically have any diagnostics monitoring the DP's read. If a traditional DP transmitter is saturated, the PLR value read is larger than in reality. If a PPL DP transmitter is saturated, the PLR value read is lower than in reality. Hence, with no diagnostics, these metering systems can use this erroneous PLR measurement to predict too high or too low a Lockhart Martinelli parameter. The larger the read PLR the wetter the flow is believed to be and vice-versa. (That is, these systems inherently assume any PLR reading to be correct, and any shift in the PLR to be due to Lockhart Martinelli parameter changes only.) For the case of a saturated traditional DP transmitter the apparent gas mass flow rate prediction is low as the input traditional DP is low. Therefore, too low an apparent gas mass flow prediction is then being over-corrected by a falsely high prediction of the Lockhart Martinelli parameter. Therefore, a saturated DP transmitter reading the traditional DP has the potential to cause the compound errors of an artificially low apparent gas mass flow rate being over corrected by an artificially high Lockhart martinelli parameter. Hence, with wet gas flow a saturated traditional DP transmitter can induce significant gas flow rate prediction errors.

The diagnostics have the ability to identify an incorrect DP measurement when a Venturi meter is in use with wet gas flow and warn the operator. In dry gas flow applications issues regarding the measurement of DP's are indicated by monitoring of the NDB. In the particular case of wet gas flow this method will not in itself identify a DP transmitter problem. Wet gas flow has a very large influence on the diagnostic points (e.g. see Figure 25). Therefore, if a DP transmitter has a relatively small problem, such as drift or a slightly saturated DP transmitter, the effect on the NDB plot is dwarfed by the wet gas flow effect. Hence, for wet gas flow the NDB is not the primary monitoring system for DP transmitter issues. Instead there is a simple and effective alternative check that also exists as part of the diagnostic system.

Equation 1 is a consequence of the first law of thermodynamics. It is not possible for any physical occurrence to violate this law. True DP's created by any flow (including wet gas flow) through the Venturi meter must be such that equation 1 holds true. However,

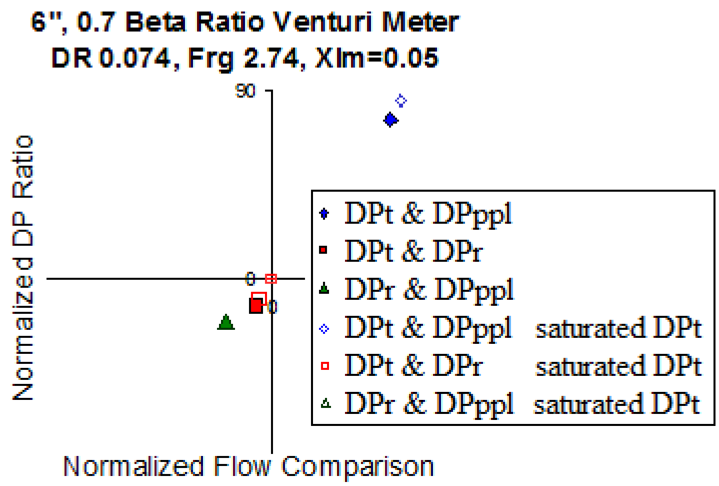


Fig 28. A saturated traditional DP transmitter example.

equation 1 does not **appear** to hold when the instruments measuring the DP's have a problem. A malfunctioning DP transmitter can falsely state **any** DP. Hence, a diagnostic check on the validity of the DP's being read through the Venturi is to check that the three read DP's agree with equation 1. This very simple check is powerful and not usually carried out by industry. It is carried out by Prognosis.

Figure 28 shows a sample case for where a gas to liquid density ratio of 0.074, a gas densiometric Froude number of 2.7 and a Lockhart Martinelli parameter of 0.05 gave an actual traditional DP read of 54.6"WC / 13.58kPa. With a PPL of 4.36kPa the PLR was 0.321 (compared to the dry gas value of 0.067 stated in Figure 21). The wet gas over-reading was 12.9%. The diagnostic plot is shown as solid points. Now, let us consider the hypothetical case when the traditional DP transmitter is saturated at an upper range limit of 50"WC / 12.44kPa. Here the PLR would falsely be read as 0.35 instead of the correct 0.321 (i.e. +9% PLR error). Figure 28 shows the resulting diagnostic plot with hollow points. The traditional DP & PPL point is further from the origin than the correctly read point. If the PLR is monitored with no diagnostics this suggests the flow is wetter than it actually is. (The traditional to recovery DP pair move in the opposite direction to an increasing liquid loading, suggesting the problem is not increasing liquid loading. However, standard wet gas Venturi meters have no diagnostics so this would be missed.)

There is no traditional method of checking for saturated DP transmitters in dry or wet gas flow (other than due diligence). If the NDB plot alone is used then a saturated DP transmitter with wet gas flow may go unnoticed. As the gas flow rates increase, any shift in the diagnostic points due to a saturated traditional DP maintaining a constant value while the other two DP's increase could be falsely interpreted as an increase in the Lockhart Martinelli parameter. However, the diagnostics also check equation 1. In this example the actual DP's read were a traditional DP of 54.6"WC / 13.58kPa, a recovered DP of 36.9"WC / 9.18kPa and a PPL of 17.5"WC / 4.36kPa. Therefore we have:

9.18 kPa + 4.36 kPa = 13.54 kPa (inferred) Compared to traditional DP measurement of 13.58kPa -0.3 % difference in measured and inferred traditional DP's. Typically if there is a difference < 1% no DP reading warning is given.

However, if the traditional DP is saturated at 50"WC / 12.44kPa we have:

9.18kPa + 4.36 kPa = 13.54kPa (inferred) Compared to traditional DP measurement of 12.44kPa +8.8% difference in measured and inferred traditional DP's. Typically if difference > 1% warning given.

Note however that this check is only possible if the **three** DP's are individually read. The issue of saturating a DP transmitter can apply to any DP transmitter. For Lockhart Martinelli parameter monitoring, and for the more sophisticated techniques of attempting to use the PLR to predict the Lockhart Martinelli parameter and therefore the actual gas flow rate through some wet gas correlation, an incorrect PPL reading will also have knock on effects. Therefore, in the final example we consider a saturated PPL DP transmitter. Let us consider the same flow condition as before. However, let us consider the scenario of the PPL DP transmitter being saturated at 4kPa. The read PLR would be 0.295 instead of the actual PLR of 0.321. Hence, the PLR is being under read by -8.25%. This could lead the Venturi meter wet gas flow system to indicate that the Lockhart Martinelli parameter is less than it actually is. Figure 29 shows the NDB plots for this flow condition when the PPL is correctly and incorrectly read due to a saturated PPL DP transmitter.

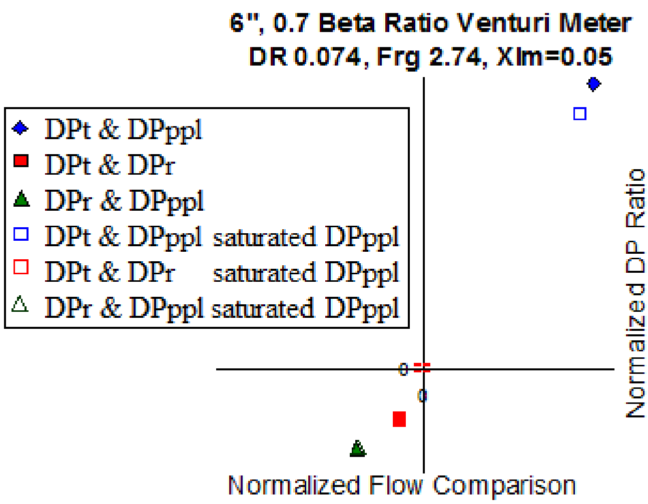


Fig 29 . A saturated PPL DP transmitter example.

Again the wet gas influence on the NDB plot is an order of magnitude larger than the saturated DP transmitter issue and hence the saturated PPL DP transmitters affect on the NDB plot is masked by the wet gas flow effect. However, if the three DP's are individually read, again the check of equation 1 clearly indicates the problem.

9.18kPa + 4.00 kPa = 13.18kPa (inferred) Compared to traditional DP of 13.58kPa -2.94% Difference in measured and inferred traditional DP's. Typically if difference > 1% warning given.

Hence, for cases where the three DP's are individually read, the diagnostics check equation 1. Any significant problem with an individual DP measurement is therefore found and highlighted. Any issue with the correct reading of the PLR with wet gas flow will be noticed. Therefore, DP reading issues can be seen even if the flow is wet gas flow. Unlike traditional generic PLR monitoring systems for wet gas flow meters, PLR reading errors will not be interpreted by Prognosis as changes in the Lockhart Martinelli parameter.

6. Conclusions

The four Centrica ISO compliant Venturi meters were fully calibrated at the GL Flow Centre to find their individual discharge coefficients and the other diagnostic parameters. These third party manufactured Venturi meters, tested at the third party test facility for a third party user were found to behave as DP Diagnostics had predicted. That is, the three flow coefficients and the three DP ratios were found to be practicable parameters for use in industry and all four Venturi meters had each of the six diagnostic parameters fitted to the same uncertainty ratings.

With no diagnostic tests conducted at the GL Flow Centre DP Diagnostics has been able to do virtual diagnostic tests by manipulating the calibration data. It has been shown that the diagnostics are capable of distinguishing between three nominally identical Venturi meters. Traditionally there is no practical method of telling nominally identical Venturi meters apart. Hence, this ability gives industry for the first time a technical method of guarding against human error involved in calibrating batch Venturi meters.

The diagnostics have been shown to be able to monitor for incorrect keypad entries of inlet or throat diameters. The diagnostics identify when there is a Venturi meter flow rate prediction error due to erroneous DP measurements such as a saturated, incorrectly spanned or drifting DP transmitter, or when an impulse line is blocked. The diagnostics can identify a flow prediction error if there is wet gas flow through a Venturi meter. However, unlike with standard wet gas flow Venturi meters, the addition of the diagnostics can identify if a PLR shift is due to a wet gas flow condition change or due to a DP reading error. The Prognosis software presents much of this information in a user friendly simple picture.

The diagnostics can see most flow prediction errors well within 2% of the actual flow rate value. With a Venturi meter typical uncertainty rating of 1% this means that the diagnostics can see most common Venturi meter malfunctions within 1% of the stated meters performance.

6. References

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