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NATURAL GAS PRODUCTION FLOW METERING WITH VENTURI METERS
A DISCUSSION ON OPERATION WITH ADVERSE UPSTREAM NATURAL GAS FLOW CONDITIONS

Richard Steven[1], Charles Britton[2]

Abstract

It is often necessary during natural gas production to meter flows before they are processed. This can be a challenging application for flow meters. Such flows can contain particulates that can contaminate instruments or erode equipment. Some unprocessed flows may also be wet gas flows, i.e. water and hydrocarbon liquids are entrained in the gas flow. This can cause both gas flow rate prediction errors and flow assurance problems due to water presence having the potential to cause hydrate, scale and salt deposits. Venturi meters are a popular choice for such applications due to Venturi meters being relatively sturdy, simple, reliable and relatively inexpensive. In this paper the effect of wet gas flow on gas Venturi meters will be discussed. A Venturi meter diagnostic system to monitor the meters health in these adverse flow conditions will also be presented.

1. Introduction

Flow metering of unprocessed natural gas production flows is important for several reasons. A flow meter informs the operator of the actual production rates and therefore the cash flow from the asset. However, there are other benefits. Accurate flow rate prediction allows the reservoir engineers to predict well depletion and therefore better control long term production rates to maximize asset profitability. Flow meters in pipes heading to the communal pipe work of a gas processing terminal inlet aid in allocation agreements among partners. Finally, an indication of a malfunctioning flow meter can be the earliest warning system that a pipe line has a potentially serious problem (such as blockage by scale, salts or hydrate deposits) that requires intervention if continued production is to be assured.

Natural gas flow metering upstream of the process plant is a challenging but necessary undertaking. Such flows can be wet gas flows (i.e. mixes of gas, water and oil) and have a tendency to have the water related issues of scale, salts and hydrates. In this adverse environment the Venturi meter is one of the most popular meters, due to it being sturdy, inexpensive and reliable. However, it is not immune to the adverse conditions. In this paper Venturi meter performance in upstream natural gas production pipelines is discussed.

2. Venturi Meter Principles

Venturi meters read the inlet pressure (P_1) and one differential pressure or "DP" (ΔP_t), that is, the difference in pressure between the pressure at the inlet pressure tap (1) and the pressure (P_t) at the low pressure tap in the minimum cross sectional area, or "throat" (t), as shown in Figure 1. Figure 1a shows a simplified sketch of the pressure field through a Venturi meter. Traditionally, the Venturi meter gives one flow rate prediction as shown in equation 1:

$$\dot{m}_t = EA_t \varepsilon C_d \sqrt{2\rho_g \Delta P_{t_{gas}}} \quad , \qquad \text{uncertainty} \pm x\% \tag{1}$$

Note $\dot{m}_t$ represents the traditional mass flow rate equation prediction of the actual gas mass flow rate. The symbol ρ_g represents the gas density. Symbols E and A_t represent the velocity of approach (a constant for a set meter geometry) 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 the expansion factor is unity.

[1] DP Diagnostics, PO Box 121, Windsor, Colorado 80550, rsteven@dpdiagnostics.com

[2] CEESI, Weld County Road 37, Nunn, Colorado 80648, cbritton@ceesi.com

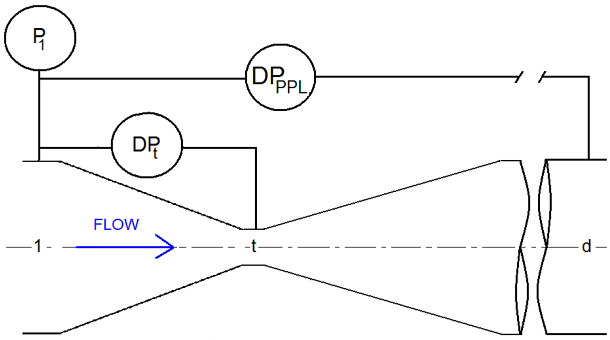

Fig 1. A sketch of an ISO standard Venturi meter

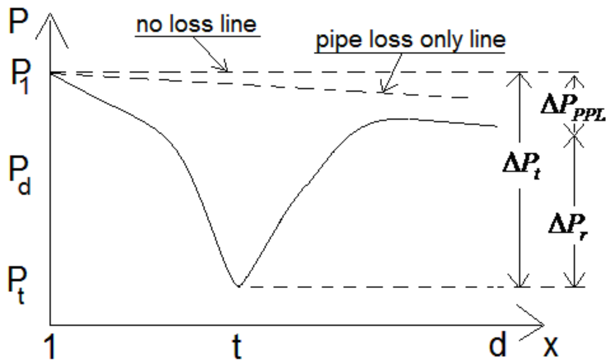

Fig 1a. Pressure fluctuation through Venturi meter.

For gases the Venturi meter uses the theoretical isentropic expansion factor as shown as equation 2. Note that κ is the gases isentropic exponent, τ is the ratio of the throat to inlet pressure and β is the beta ratio, i.e. a meter specific geometric constant.

$$\varepsilon = \sqrt{\left(\frac{\kappa\tau^{2/\kappa}}{\kappa-1}\right)\left(\frac{1-\beta^4}{1-\beta^4\tau^{2/\kappa}}\right)\left(\frac{1-\tau^{\frac{\kappa-1}{\kappa}}}{1-\tau}\right)} \quad (2)$$

The term C_d represents the discharge coefficient. If the meter geometry and application flow conditions are compatible with the ISO 5167 [1] geometry and the ISO flow condition ranges then the Venturi discharge coefficient is usually taken to be that which ISO predicts. If they are not compatible the discharge coefficient is required to be found by calibration. Any Venturi flow meter discharge coefficient statement must be accompanied with an associated uncertainty rating ($x\%$). For a detailed derivation of the standard Venturi meter flow equation see Steven [2].

2.1 Venturi Flow Meter Calibration vs. ISO Predictions

Predictions for Venturi meter discharge coefficients over set flow condition ranges are given by ISO 5167 Part 4 [1]. However, although many in industry tend to use these predictions for all Venturi meter applications, the flow condition ranges covered by this standard are actually rather limited. That is, it should be noted that ISO 5167 is only valid over set ranges of Venturi meter geometries and flow conditions. For example, ISO 5167 includes a discussion on the high precision machined convergent section Venturi meter. This is the Venturi meter type primarily used in natural gas flow production. The limits of this meters ISO performance declaration are:

50 mm (2") ≤ D ≤ 250 mm (10")
0.4 ≤ β ≤ 0.75
2e5 ≤ Inlet Reynolds Number (D) ≤ 1e6

Many industrial natural gas flow conditions have meter sizes and application flow conditions out with these limits of the ISO Venturi meter standard. Extrapolating the ISO discharge coefficient prediction to other conditions is a relatively common practice but it is not technically valid. ISO 5167 states that as long as the Venturi meter is within the geometry and flow condition range discussed the discharge coefficient is a constant, i.e. $C_d = 0.995$ to an uncertainty of ±1%. However, ISO 5167 also states:

"Research into the use of Venturi tubes in high-pressure gas [≥ 1 MPa (≥ 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. For optimum accuracy Venturi tubes for use in gas should be calibrated over the required flow rate range."

Furthermore, ISO also explain that a simultaneous use of the limits extreme values of D, β, Re(D) shall be avoided as otherwise the Venturi meter flow rate uncertainty is likely to increase. They therefore state that for installations outside these diameter, beta ratio, pressure and Reynolds number limits, it remains necessary to calibrate the meter in its actual conditions of service.

Most natural gas production pipe lines have pressures greater than 10 bar (abs) 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.

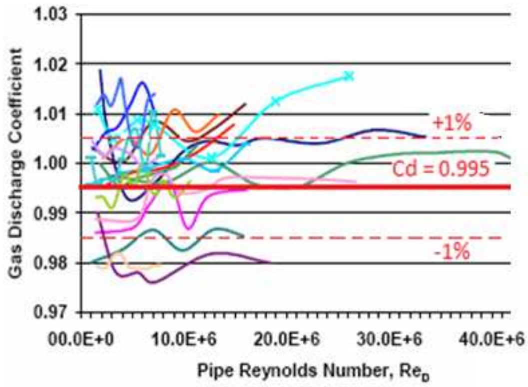

Fig 2. Eighteen ConocoPhillips Venturi meter data sets.

Figure 2 shows a reproduction of massed Venturi meter gas flow calibration results shown by Geach [3] in 2005. Note that the size range was a diameter range of 6” to 10” and a beta ratio range of 0.48 to 0.7. Hence, all these meters were within the geometry range of the ISO Venturi meter discharge coefficient prediction. However, the data sets were for pipe Reynolds numbers greater than one million, i.e. higher than the upper limit of the ISO range. Superimposed on the graph is the ISO discharge coefficient prediction for these Venturi meters extrapolated to the higher Reynolds numbers conditions. Clearly many of the meters do not have performances that matched the extrapolated ISO discharge coefficient predictions.

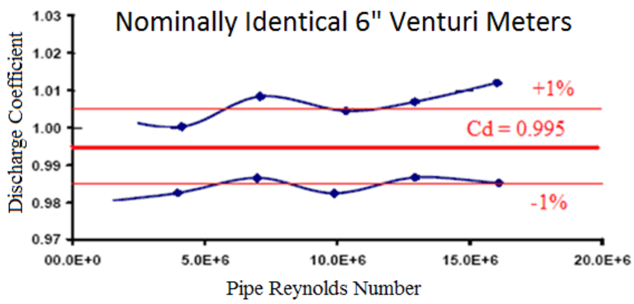

Fig 3. Nominally identical 6” ISO compliant Venturi meters compared to each other.

It has also been noted that nominally identical Venturi meters built by the same manufacturer to the same drawing, to the same machining tolerance with the same fabrication equipment can have different performances. Figure 4 show the result of two such nominally identical Venturi meters being calibrated. The meters were stated to be ISO compliant 6” Venturi meters but the beta ratio was not disclosed. There is approximately a 2% difference in the discharge coefficient between the meters. As the ISO discharge coefficient prediction is often simply extrapolated this is shown in Fig 3. For one meter the extrapolated ISO prediction is approximately 1% low and for the other it is 1% high, with some points exceeding the users expected 1% uncertainty limit. The blind application of extrapolated ISO stated discharge coefficient predictions can lead to flow measurement errors. Therefore, for low flow rate uncertainty, Venturi meters with flow conditions outside the limited ISO scope should be individually calibrated across the full Reynolds number range of the meters application.

3. Wet Gas Response of Venturi Meters

If a Venturi meter is operated with a wet gas flow, the liquid presence affects the differential pressure read. This wet gas / two-phase flow differential pressure ($\Delta P_{t_{wet}}$) is higher than the differential pressure that would have been read if the gas flowed alone (ΔP_{t_g}). The application of this wet gas DP value in the gas flow equation 1 results in an incorrect high gas mass flow rate prediction. This often called the *apparent* gas mass flow, $\dot{m}_{g,apparent}$.

Wet gas flow is defined here as any gas and liquid flow that has a Lockhart-Martinelli parameter, X_{LM}, less than 0.3 [3]. The Lockhart-Martinelli parameter is a non-dimensional description of the wetness of the gas and is defined by equation 3. Here ρ_l represents the liquid density and $\dot{m}_l$ represents the liquid mass flow rate.

$$X_{LM} = \frac{\dot{m}_\lambda}{\dot{m}_g}\sqrt{\frac{\rho_g}{\rho_\lambda}} \qquad (3)$$

Venturi meters have responses to wet gas flow that are dependent on the gas to liquid density ratio (which is effectively a dimensionless representation of the pressure for a set liquid component). The gas to liquid density ratio is indicated by *DR*:

$$DR = \rho_g / \rho_\lambda \qquad (4)$$

The gas densiometric Froude number (equation 5) is a non-dimensional gas velocity. In this equation, *g* is the gravitational constant (9.81m/s^2), A represents the meter inlet area and D represents the meter inlet diameter.

$$Fr_g = \frac{\dot{m}_g}{A\sqrt{gD}}\sqrt{\frac{1}{\rho_g\left(\rho_l - \rho_g\right)}} \qquad (5)$$

Note that the equations above all assume one liquid component. However, in wet natural gas flow production there is often hydrocarbon liquid and water present with the natural gas. In such cases the combined liquid flow, i.e. the sum of the hydrocarbon liquid ($\dot{m}_{hl}$) and the water ($\dot{m}_w$) flow rates, is commonly ***assumed*** at typical hydrocarbon production conditions to be well enough mixed to be considered a homogenous liquid. In this case averaged liquid properties are often assumed. Water cut ("WC") is defined by ASME [4] as the "water volume to total liquid volume flow rate ratio *at standard conditions*". However, flow meters operate at *flowing conditions*. The water volume to total liquid volume flow rate ratio at flowing conditions is generally called the WLR (i.e. water liquid ratio). There is a tendency for the phrases WLR and water cut to be used as equivalent terms as the difference between WC and WLR is small due to liquid having extremely small density changes over large pressure changes.

Venturi meters with wet gas flows have a positive bias or *over-reading* on their gas flow rate prediction. That is, the uncorrected gas mass flow rate prediction (i.e. the apparent gas mass flow, $\dot{m}_{g,apparent}$) is usually greater than the actual gas mass flow rate of the wet gas flow. The "over-reading" is the ratio of the apparent to actual gas flow rate. This term is usually expressed as a percentage. Equation 6 shows the percentage over-reading (OR).

$$OR\ (\%) = \left(\frac{\dot{m}_{g,apparent}}{\dot{m}_g} - 1\right) * 100\% \cong \left(\sqrt{\frac{\Delta P_{t_{wet}}}{\Delta P_{t_{gas}}}} - 1\right) * 100\% \qquad (6)$$

Figure 4 shows a 4", schedule 80, 0.6 beta ratio Venturi meter installed in the CEESI wet natural gas flow loop. Flow is from left to right. Upstream of the meter is a view port and camera. A similar view port and camera installation is shown for clarity in Fig 5. The CEESI wet gas flow loop can flow natural gas at pressures between 15 bar and 75 bar and for 4" pipe at gas velocities up to 25 m/s (i.e. a volume flow rate of 650 m^3/hr). The liquid injection can be water, light hydrocarbon liquid or a mix of both liquids. Each liquid type can be injected at up to 14 m^3/hr, either separately or together. Meters under test can be installed in any orientation. In this paper due to space consideration only horizontal flow is considered.

Fig 4. Venturi meter in the CEESI wet gas facility.

Fig 5. Close up of CEESI wet gas flow view port.

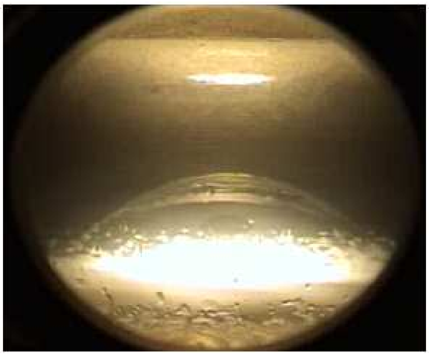

Fig 6a. Gas & water, separated flow.

Fig 6b. Gas & HCL, mist flow.

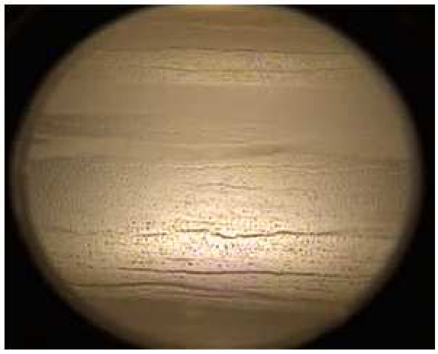

Fig 6c. Multiphase, transitional flow

Figures 6a to 6c show sample stills of various wet natural gas conditions flowing left to right. Fig 6a shows natural gas with water 60 Bara, a gas velocity of 4.5 m/s and a low liquid loading of 0.025 Lockhart Martinelli Parameter. This corresponds to a Gas Volume Fraction (or "GVF") of approximately 99.4% (i.e. at these particular conditions 0.6% of the total volume flow is that of the liquid phase). The WLR is 100%. Here the two-phase wet gas flow pattern (i.e. the physical dispersion of the liquid in the pipe) is a separated flow, i.e. the liquid runs along the base of the pipe. Fig 6b shows natural gas with kerosene at 75 Bara, a gas velocity of 25 m/s and a moderate liquid loading of a 0.15 Lockhart Martinelli Parameter. This corresponds to a Gas Volume Fraction of approximately 97.3% (i.e. at these particular conditions 2.7% of the total volume flow is that of the liquid phase). The WLR is 0%. Here the two-phase wet gas flow pattern is a mist flow, i.e. the liquid flows in droplets entrained in the gas with a wetted pipe wall. Fig 6c shows natural gas with water and kerosene flowing together. The pressure is 15 bar and the gas velocity is 18 m/s. The liquid loading is a Lockhart Martinelli parameter of 0.15, i.e. a GVF of 97.9% (i.e. at these particular conditions 2.1% of the total volume flow is that of the liquid phase). The WLR is 75%, i.e. 75% of the liquid phase is 75% water by volume. Here the "multiphase" wet gas flow pattern is transitional flow between separated and mist flow. Furthermore, the water is seen to collect on the wall and run along the pipe wall in streaks.

Wet gas flow patterns are known to have a very significant affect on a Venturi meters wet gas over-reading. The multiphase wet gas flow data set taken at CEESI for the test of the 4", schedule 80, 0.6 beta ratio Venturi meter shown in Fig 4 is shown in Fig 7. The graph is a plot of the liquid loading (i.e. Lockhart Martinelli parameter) vs. % over-reading. The data is split up by average gas to liquid density ratio and gas densiometric Froude numbers. Clearly the presence of liquid greatly affects the gas meters gas flow rate prediction. For heavy liquid loadings the meter can be in error by greater than 60%. A distinct gas to liquid density ratio (i.e. pressure) effect can be seen. The higher the gas to liquid density ratio for all other parameters held constant, the lower the wet-gas over-reading. A gas densiometric Froude number effect exists but is not as clear to see as the gas to liquid density ratio effect, partially as it is masked by a WLR effect. The higher the gas densiometric Froude number for all other parameters held constant, the higher the wet-gas over-reading. This can be seen for example when comparing the higher gas to liquid density ratio data sets with Lockhart Martinelli parameters of approximately 0.05. For a set gas to liquid density ratio of 0.065 as the gas densiometric Froude number increases from 1.2

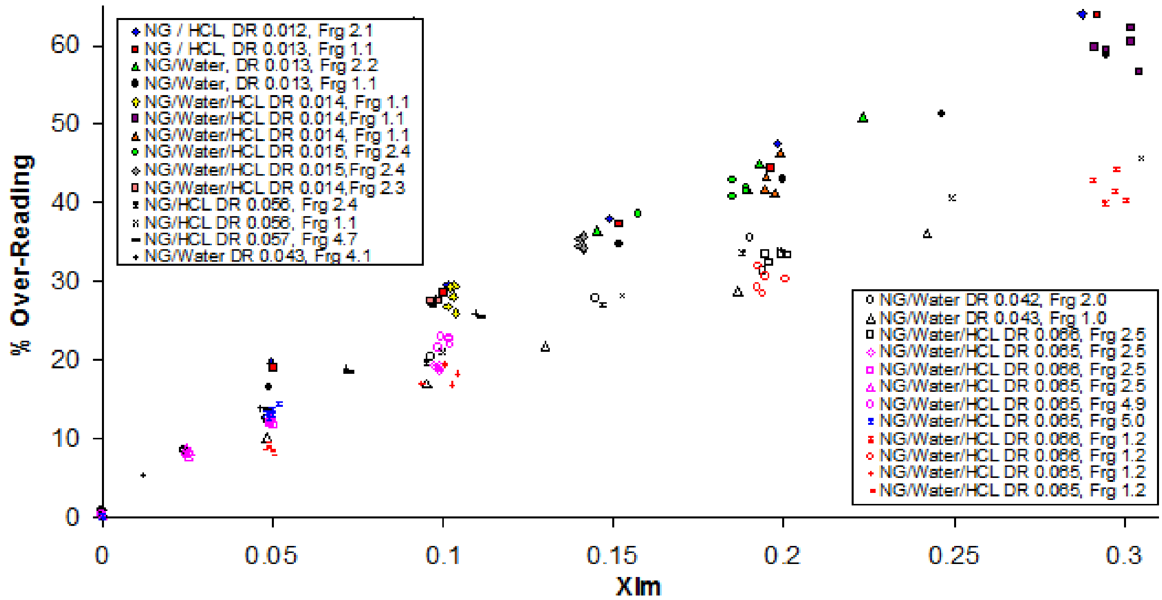

Fig 7. CEESI wet gas flow test data for a 4", schedule 80, 0.6 beta ratio horizontally installed Venturi meter.

(red dash) to 2.5 (pink box) & then 5 (blue star) the over-reading is seen to increase. Note that all data points seem to have a cluster of data. This is only partially scatter in the data set. Much of this apparent scatter is down to the fact that each of these "set" data points are actually for a range of WLR's from 0% to 100%. The WLR effect on the over-reading is not yet well understood. However, it is clearly understood that liquid presence with the gas induces a positive bias (or "over-reading") on the Venturi meter gas flow rate prediction. This can be a significant error, even for small liquid loadings. For example, even at a Lockhart Martinelli parameter of 0.012, a gas to liquid density ratio of 0.043 and a gas densiometric Froude number of 4.1 (where for these conditions the GVF is 99.75% - i.e. there is only 0.25% by volume flowing of liquid) the gas flow rate over-reading is approximately 5.8%. (This point is shown in Fig 7 as the black cross closest to the origin.)

Over-reading the natural gas flow rate is not the only problem caused by natural gas flows being wet. Water in the liquid phase can cause hydrate formation which can potentially block the flow line thereby causing flow assurance issues. (Scale and salt deposits are other water induced problems that can cause flow assurance issues). Figures 8a shows hydrates being deliberately produced in a wet gas flow at CEESI for research purposes. The horizontal natural gas and water flow is left to right. Fig 8b shows the results of hydrate formation not being noticed and dealt with in an offshore production line. The pipeline production was lost due to a complete pipe blockage.

Fig 8a. Wet gas flow hydrate formation.


Fig 8b. Hydrate plug in a production line.

4. Venturi Flow Meter Diagnostic Capabilities

Diagnosing when a Venturi meter in operation with natural gas flows has a problem is important both in terms of accurate flow measurement and flow assurance. Traditionally Venturi meters have no built in diagnostic capability. The following discussion describes a new patent pending diagnostic system for Venturi meters.

Fig 1a shows the pressure field through a Venturi meters body. Note that Fig 1 shows a Venturi meter with a downstream pressure tap. This allows the measurement of three DP's, i.e. the traditional DP (ΔP_t) between the upstream and throat, the permanent pressure loss, or "PPL" (ΔP_{PPL}), between the upstream and the downstream pressure taps and the recovered DP (ΔP_r) between the downstream and throat pressure taps. The relationship between these three DP's is shown by equation 7. Note that due to this relationship all three DP's can be found by the use of one extra DP transmitter and the third DP can be derived from equation 7.

$$\frac{\Delta P_r}{\Delta P_t} + \frac{\Delta P_{PPL}}{\Delta P_t} = 1 \qquad (7)$$

Note that the ratio of the permanent pressure loss to the traditional DP is called the Pressure Loss Ratio, or "PLR". Traditionally one DP is read and one flow rate equation exists (i.e. equation 1). However, with the reading of three separate DP's three separate flow rate predictions can be made. That is, each DP can be related independently to the flow rate. The two extra flow rate equations were derived in detail by Steven [2] and are called the "expansion" and "PPL" flow rate equations. These are shown here as equations 8 & 9. Note the equations have associated uncertainties y% & z%.

$$\dot{m}_r = EA_t K_r \sqrt{2\rho \Delta P_r} \;, \qquad \text{uncertainty} \pm y\% \qquad (8)$$

$$\dot{m}_{ppl} = AK_{PPL} \sqrt{2\rho \Delta P_{PPL}} \;, \qquad \text{uncertainty} \pm z\% \qquad (9)$$

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 gas mass flow rate ($\dot{m}_g$) respectively. A represents the inlet cross sectional area. 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 Venturi 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). Note that (as explained in section 2.1) for most natural gas production flow conditions Venturi meters require calibration. Therefore, to add an extra pressure tap and an extra DP transmitter to produce a diagnostic capable Venturi meter is little more effort or expense that the standard Venturi meters calibration procedure.

Every Venturi 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%). Therefore, even if a DP 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. $\phi\% = x\% + z\%$, $\xi\% = x\% + y\%$ & $\upsilon\% = y\% + z\%$. This allows a self diagnosing system. If the percentage difference between any two flow rate equations is less than that equation pairs summed uncertainties (found from the meters calibration), then no potential problem is found and the traditional flow rate prediction can be trusted. If however, the percentage difference between any two flow rate equations is greater than that equation pairs summed uncertainties then this indicates a metering problem and the flow rate predictions should not be trusted. The three flow rate percentage differences are calculated by equations 10a to 10c.

Traditional to PPL Meter Comparison :
$$\psi\ \% = \left\{ \left(\dot{m}_{PPL} - \dot{m}_t \right) \Big/ \dot{m}_t \right\} * 100\% \qquad (10a)$$

Traditional to Expansion Meter Comparison:
$$\lambda\ \% = \left\{ \left(\dot{m}_r - \dot{m}_t \right) \Big/ \dot{m}_t \right\} * 100\% \qquad (10b)$$

PPL to Expansion Meter Comparison:
$$\chi\ \% = \left\{ \left(\dot{m}_r - \dot{m}_{PPL} \right) \Big/ \dot{m}_{PPL} \right\} * 100\% \qquad (10c)$$

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 PLR is constant for all Venturi meters operating with single phase homogenous flow. From equation 7, if PLR is a constant set value then both the **P**ressure **R**ecovery **R**atio or "PRR", (i.e. the ratio of the recovered DP to traditional DP) and the **R**ecovered DP to **P**PL **R**atio, or "RPR" must then also be constant set values. That is, all DP ratios available from the three DP pairs are constant values for any given DP meter geometry and can be found by the *same* calibration that finds the three flow coefficients. Thus we also have:

$$PLR_{cal} = (\Delta P_{PPL} / \Delta P_t)_{cal} , \quad \text{uncertainty} \pm a\% \tag{11a}$$

$$PRR_{cal} = (\Delta P_r / \Delta P_t)_{cal} , \quad \text{uncertainty} \pm b\% \tag{11b}$$

$$RPR_{cal} = (\Delta P_r / \Delta P_{PPL})_{cal} , \quad \text{uncertainty} \pm c\% \tag{11c}$$

Here then is another method of using the three DP's to check a DP 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 $\eta\%$.

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 (± ϕ%, ± ξ , ± υ%). ***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 an alarm. Note that each of the six diagnostic checks has ***normalized data***, i.e. each meter diagnostic parameter output is divided by the allowable difference for that parameter.

DP Pair	No Alarm	ALARM	No Alarm	ALARM
ΔP_t & ΔP_{ppl}	$\psi\% / \phi\% \le 1$	$\psi\% / \phi\% > 1$	$\alpha\% / a\% \le 1$	$\alpha\% / a\% > 1$
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.

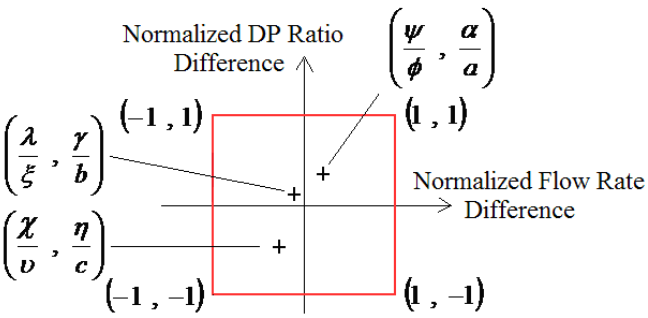

Fig 9. A normalized diagnostic calibration box with normalized diagnostic result.

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, DP Diagnostics proposed that the three points be plotted on a normalized graph (as shown in Fig 9). 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 calibrations maximum allowable differences. 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 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 Fig 9 all points are within the NDB indicating the meter is operating within the limits of normality, i.e. no metering problem is noted.

4.1 Venturi Flow Meter Diagnostic System Test Results

The 4", 0.6 beta ratio Venturi shown in Fig 4 was calibrated with dry natural gas flow. A downstream pressure tap (located 6 diameters downstream of the meter) allowed the PPL to be recorded during calibration thereby allowing the meter to be made diagnostic capable. In all examples here the recovered DP was subsequently found with equation 7. Fig 10 shows the calibration results. Fig 11 shows the calibration points on the diagnostic NDB plot. Note all the calibration data is inside the NDB indicating that the meter is operating correctly. This is in itself a trivial result. The uncertainties of the six parameters were set by the very calibration data now plotted on the graph so by consequence all resulting calibration data ***must*** be inside the NDB. However, once a full calibration has allowed all the Venturi meters characteristics to be known as shown in Fig 10, it is possible to set up such a NDB plot to monitor the meters performance in its application, i.e. once there is no reference meter available. Traditionally in this situation there are no diagnostic methods available for Venturi meters. However, using this described method gives the meter simple but very effective diagnostics.

4", 0.6 beta ratio Venturi meter

$C_d = 1.003$ $x = 1\%$ $\phi\% = x\% + z\% = 2\%$

$K_r = 1.071$ $y = 1.03\%$ $\xi\% = x\% + y\% = 2.03\%$

$K_{PPL} = 1.03$ $z = 1\%$ $\upsilon\% = y\% + z\% = 2\%$

$PLR = 0.1395$ $a = 4\%$

$PRR = 0.8572$ $b = 2\%$

$RPR = 6.191$ $c = 4\%$

Fig 10. CEESI Venturi meter full calibration results.

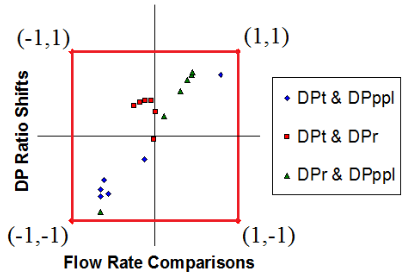

Fig 11. Correctly operating meter diagnostic plot.

Example 1: **A wet gas flow**: Fig 12 shows the diagnostic response to wet gas flow. In this example 0.34 kg/s fresh water is entrained with the natural gas flow of 5.91 kg/s. The pressure is 55.9 Bar, the temperature 304K and the gas density is 42.6 kg/m3. This is a GVF of 99.75%, i.e. a Lockhart Martinelli parameter of 0.012. (In fact this wet gas flow data point is the lowest liquid loading of the data set shown in Fig 7.) The liquids presence affects the traditional DP being produced. The resulting uncorrected gas flow rate prediction from the Venturi meter has a +5.8% liquid induced error.

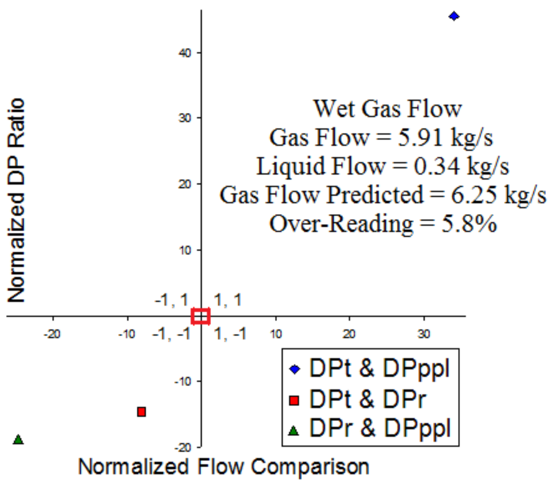

Fig 12. Wet gas flow diagnostic example.

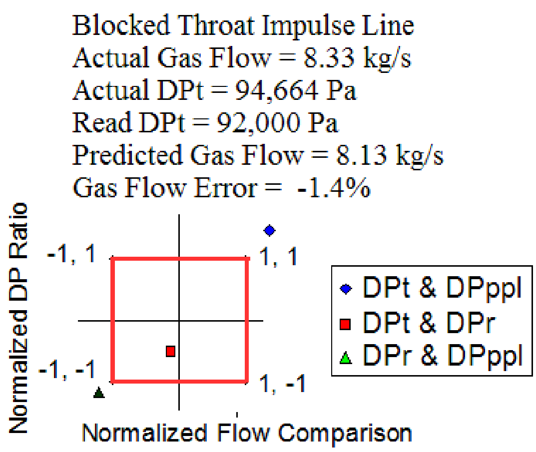

Fig 13. A blocked impulse line diagnostic example.

Fig 12 clearly shows that the diagnostics are very sensitive to even small liquid quantities being present in the gas stream. Whereas in Fig 11 for a correctly operating meter the diagnostic points were all inside the NDB, here for wet gas flow they are so far from the NDB that the box is shrunk to the centre of the plot. Note that the liquid loading was not particularly high compared to many actual wet gas flow conditions found in the natural gas production industry. However, the meter had a 5.8% positive bias (or "over-reading") and the diagnostic check had a dramatic result showing the system was very far from operating according to the single phase flow response.

Example 2: **A blocked pressure port / impulse line.**: When Venturi meters operate in wet gas flow a possible malfunction is the blocking of a pressure port entrance or impulse line (i.e. the tubing that connects the pressure port and DP transmitter). A blockage can occur due to particulate, hydrate, scale or salt build up. This blockage can occur even with periodic small quantities of water being present and if a problem can be identified with the Venturi meter this can be one of the earliest warnings of a future flow assurance issue.

In this example we consider a real dry natural gas data point where 8.33 kg/s of gas flowed at density of 44.6 kg/m^3 through the 4", 0.6 beta ratio Venturi meter shown in Fig 4. The correctly read traditional DP read was 94,664 Pa. However, let us imagine that the throat pressure port had been blocked up at an earlier time when the throat pressure was slightly higher and the gas flow rate slightly lower. At the present time the inlet pressure is the same as it was but the gas flow rate has increased and the actual throat pressure has therefore reduced. However, due to the blockage the pressure in the throat impulse line remains trapped as it was at the moment of blockage. Therefore, the transmitter sees an artificially low traditional DP. Here let us say the traditional DP read by the transmitter is a round 92,000 Pa. This makes the meter under predict the gas flow rate by approximately 1.4%. Traditionally there are no diagnostic methodologies internal to a Venturi meter that could indicate such an error exists. However, this flow condition plotted live on a NDB plot would give the diagnostic pattern shown in Fig 13.

Fig 13 clearly shows that the diagnostics are sensitive to even small blockages in the impulse lines producing false DP readings. Whereas in Fig 11 for a correctly operating meter the diagnostic points were all inside the NDB, here for a blocked impulse line two of the three diagnostic points are out with the NDB thereby signaling that the meter has a problem. (It only takes any single point to be outside the NDB to indicate a problem.) Furthermore, it can be shown from fundamental hydraulic theory (although there is not enough space in this paper to prove it) that the diagnostic pattern in Fig 13 is not possible for any case where the three DP's are read correctly. That is, even if a meter is operating incorrectly for any reason, if the three DP's are being read correctly there are only set combinations of NDB plot patterns that don't violate the first law of thermodynamics for open systems. The plot in Fig 13 represents a combination of three DP's that is not physically possible thereby indicating that the problem is an instrumentation problem and the DP's read can not represent true DP's of a correctly or incorrectly operating meter body. This then suggests a DP transmitter malfunction or an issue with the impulse lines.

5. Conclusions

Venturi meters are used with unprocessed natural gas flows. For most gas flows Venturi meters will require calibration to ensure a 1% flow rate uncertainty. Wet gas flow causes a Venturi meter to over-read the gas flow and if the liquid contains water hydrates, scale & salts can deposit in the pipe. DP Diagnostics have created a patent pending diagnostic system for Venturi meters. This diagnostic methodology is simple but effective and of practical use for real time Venturi meter monitoring. The diagnostics will detect wet gas flow and blockages of the meters impulse lines. This diagnostic warning offers operators early warning of the potential for future hydrate, scale and salt blockages of the pipe line itself.

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