Venturi Meters, Wet Gas Flow, and the ISO TR 11583 *XLM = f(PLR)* Correlation

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1 INTRODUCTION

A seminal paper by de Leeuw [1] in 1997 showed that a standard horizontally installed Venturi meter with a downstream pressure tap and read permanent pressure loss, *PPL*, could be developed into a rudimentary wet gas flow meter (see Fig. 1). De Leeuw presented a wet gas Venturi meter correlation that predicted the liquid induced gas flow prediction bias, i.e. over-reading (*OR*), for a known liquid loading, e.g. Lockhart Martinelli parameter (X_{LM}). This correlation was *specifically* for a horizontal 4", 0.4β Venturi meter with gas and liquid hydrocarbon, $OR = f(X_{LM})$. The concept of a $X_{LM} = f(PLR)$ relationship, i.e. where the Lockhart Martinelli parameter could be predicted via the ratio of the PPL and primary DPs (i.e. the Pressure Loss Ratio, *PLR*), was also introduced, but no correlation was given.

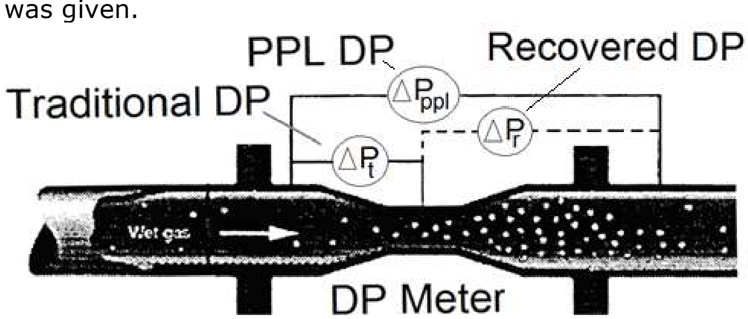


Fig 1. Venturi Meter with Downstream Pressure Tap
Primary, PPL, and Optional Recovered DP Readings (Not to Scale).

In 2009 Reader Harris et al [2] presented a general wet gas Venturi meter *OR* vs. X_{LM} correlation for ≥ 2" Venturi meters, across $0.4 \le \beta \le 0.75$, for gas with liquid hydrocarbon *or* water, across the full wet gas flow range $X_{LM} \le 0.3$. Reader Harris also presented a wet gas Venturi meter correlation that, *for a very limited wet gas flow range*, predicted the Lockhart Martinelli parameter from the Pressure Loss Ratio '*PLR*', $X_{LM} = f(PLR)$. In 2012 ISO published Reader Harris's work in ISO TR 11583 [3]. In 2015 Reader Harris et al [4] showed that this correlation could be used with gas with liquid hydrocarbon *and* water wet gas flows, and that the correlation was robust enough to be applicable to a range of light liquid hydrocarbon viscosities.

At the time of publication this ISO TR 11583 horizontal installed wet gas Venturi meter correlation was somewhat controversial. Whereas some were concerned the ISO publication of this correlation could discourage the development of more theoretical wet gas Venturi meter models, an immediate practical concern was that this ISO correlation had not been independently checked. Whereas it was very probable the correlation was sound, ideally 3rd parties should confirm the veracity of a correlation before ISO ratified it by publication. However, since publication the author knows of at least four subsequent 3rd party confirmations of this ISO TR 11583 $OR = f(X_{LM})$ correlation: Collins et al [5], Steven et al [6], van Putten et al [7], and Bjorner M et al [8]. All confirmed as expected the ISO TR 11583 wet gas Venturi meter OR = f(X_{LM}) correlation is largely sound. Collins and Bjorner also discussed respective in-house wet gas Venturi meter OR = f(X_{LM}) correlations.

However, there is a curious omission from these Reader Harris / ISO TR 11583 wet gas Venturi meter correlation check papers. They only ratify the 1st part of the correlation, i.e. OR = f(X_{LM}). They do not ratify the 2nd part, i.e. X_{LM} = f(PLR). But this 2nd part of the algorithm is the *crucial* part that turns the Venturi meter into a wet gas flow metering system. If this second correlation can predict the liquid loading across a reasonable liquid loading range then industry has a simple, ISO ratified, relatively inexpensive, public domain technology wet gas flow meter. That is, a standard ISO 5167 Venturi meter with a 6D downstream tap, reading the primary and PPL DPs, and running the ISO correlation would produce an ISO ratified wet gas meter. This would be of practical significance to industry. Reader Harris et al [4] did revisit the X_{LM}=f(PLR) correlation showing with limited data the correlation to be valid across a limited range, but useful as that result is, it is more of a repeatability check and not an independent reproducibility check, and the practical liquid loading range of the correlation remains rather obscure.

In this paper new massed wet gas Venturi meter data is introduced to check the complete ISO TR 11583 wet gas Venturi meter correlation. The practical Lockhart Martinelli parameter range of the ISO correlation is considered, and it is shown it is possible to use the wet gas Venturi meter X_{LM}=f(PLR) relationship beyond the ISO range up to $X_{LM} \leq 0.05$.

2 WET GAS FLOW METER TERMINOLOGY

Wet gas flow is defined by ISO as any liquid and gas two-phase where $X_{LM} \leq 0.3$. This definition covers any combination of gaseous and liquid components.

The Lockhart-Martinelli parameter, see equation 1, indicates the relative amount of total liquid with the gas flow. Note that m_g and m_l are the gas and liquid mass flow rates respectively (where m_l is the sum of the liquid component flow), and ρ_g & ρ_l are the gas and liquid densities respectively. The term 'liquid loading' is widely used as a qualitative term to describe the amount of liquid with a gas flow.

$$X_{LM} = \frac{m_l}{m_g}\sqrt{\frac{\rho_g}{\rho_l}} \quad (1)$$

For a given set of fluids the gas to liquid density ratio ($DR = \rho_g / \rho_l$) is a non-dimensional expression of pressure. The gas densiometric Froude number (Fr_g), see equation 2, is a non-dimensional expression of the gas flow rate, where 'g' denotes the gravitational constant, 'D' is the meter inlet diameter and 'A' is the meter inlet cross sectional area.

$$Fr_g = \frac{m_g}{A\sqrt{gD}}\sqrt{\frac{1}{\rho_g(\rho_l - \rho_g)}} \quad (2)$$

'Water cut' is the ratio of the water to <u>total</u> liquid (i.e. the sum of liquid water and liquid hydrocarbon) volume flow rates when the fluid is at ***standard*** conditions. The "water to liquid mass ratio" (or "WLR_m") is the ratio of the water mass flow (m_w) to the sum of water mass flow and liquid hydrocarbon mass flow (m_{lhc}) see equation 3.

$$WLR_m = \frac{m_w}{m_w + m_{lhc}} \quad (3)$$

The average density of a two component liquid mixture is the total liquid mass per unit liquid volume. It is commonly and reasonably assumed that two liquid components will be effectively homogenously mixed. This homogenous liquid phase ($\rho_{l,hom}$) is calculated by equation 4 where ρ_w and ρ_{lhc} are the liquid water and liquid hydrocarbon densities respectively. For multiphase wet gas flows it is this liquid mixture density that is used to calculate *DR* and Fr_g.

$$\rho_{l,\text{hom}} = \frac{\rho_w \rho_{lhc}}{\left(\rho_{lhc}\, WLR_m\right) + \rho_w\left(1 - WLR_m\right)} \tag{4}$$

Equation 5 shows the Venturi meter gas mass flow equation, where *E* is the velocity of approach (a geometric constant), A_t is the minimum cross sectional area, C_d is the discharge coefficient, ε is the expansibility factor, and ΔP_g is the primary differential pressure. Wet gas flow conditions cause a Venturi meter to produce a two-phase wet gas DP (ΔP_{tp}), and an associated two-phase expansibility (ε_{tp}) and discharge coefficients ($C_{d,tp}$). In practice $\varepsilon_{tp} C_{d,tp} \approx \varepsilon C_d$. The two-phase DP is greater than the DP produced if the gas phase flowed alone, i.e. $\Delta P_{tp} > \Delta P_g$. Hence, the wet gas flow produces an erroneous, or 'apparent', gas mass flow rate prediction, $m_{g,Apparent}$ (see Equation 6). The over-reading is expressed either as a ratio (see Equation 7) or percentage (Equation 7a) comparison of the apparent to actual gas mass flow rate.

$$m_g = EA_t C_d \varepsilon \sqrt{2\rho_g \Delta P_g} \tag{5}$$

$$m_{g_{apparent}} \approx EA_t C_d \varepsilon \sqrt{2\rho_g \Delta P_{tp}} \tag{6}$$

$$OR = \frac{m_{g\ Apparent}}{m_g} \approx \sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} \tag{7}$$

$$OR\% = \left(\frac{m_{g\ Apparent}}{m_g} - 1\right) * 100\% \approx \left(\sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} - 1\right) * 100\% \tag{7a}$$

3. ISO HORIZONTAL VENTURI METER OR=f(X_{LM}) CORRELATION CHECK

The ISO TR 11583 $OR = f(X_{LM})$ correlation is reproduced below as equation set 8 thru 12. Note that $Fr_{g,th}$ denotes the gas densiometric Froude number in the Venturi throat (see equation 11).

In 2015 Reader-Harris stated that for a known liquid hydrocarbon and water split (i.e. a given WLR_m) assuming a linear relationship between the empirical value of *H* and WLR_m gives reasonable results, i.e. see equation 13.

Parameter	Massed Test Range	ISO Stated Limits
Pressure	12.2 to 77 bara	N/A
Gas to liquid DR	0.01 < DR < 0.087	DR > 0.02
$Fr_{g,th}$ range	$Fr_{g,th} > 2$	$Fr_{g,th} > 3$
Fr_g / H	$Fr_g/H < 8.2$	$Fr_g < 5.5$
X_{LM}	$0 \le X_{LM} < 0.3$	$0 \le X_{LM} < 0.3$
Inlet Diameter	1.939" ≤ D ≤ 7.981"	D ≥ 2"
Beta	$0.4 \le \beta \le 0.75$	$0.4 \le \beta \le 0.75$
Gas / Liquid phase	Gas / HCL / Water	Gas / HCL or Gas / Water

Table 1. ISO TR 11583 $OR = f(X_{LM})$ Applicable Range and TDFS Data Set Range.

Reader Harris also commented that for wet gas flows where $WLR_m > 0$ it is perhaps preferable to use $H = 1.35$. ISO does not comment, and the differences to the gas flow prediction results produced by these choices of *H* is small.

$$\dot{m}_g = \frac{EA_t \varepsilon_{tp} C_d^* \sqrt{2\rho_g \Delta P_{tp}}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \quad \text{--- (8)} \qquad C = \left(\frac{\rho_g}{\rho_l}\right)^n + \left(\frac{\rho_l}{\rho_g}\right)^n \quad \text{--- (9)}$$

$$C_d^* = 1 - \left(0.0463 * \left[\exp\left(-0.05 * Fr_{g,th}\right)\right] * \left\{\min\left(1, \sqrt{\frac{X_{LM}}{0.016}}\right)\right\}\right) \tag{10}$$

$$Fr_{gas,th} = Fr_g \Big/ \beta^{2.5} \tag{11}$$

$$n = \max\left(\left(0.583 - 0.18\beta^2 - 0.578\exp\left(-0.8 * Fr_g / H\right)\right),\ 0.392 - 0.18\beta^2\right) \tag{12}$$

H is 1 for light hydrocarbon liquid
H is 1.35 for water at ambient temperature
H is 0.79 for water at elevated temperatures

Stated Limits of Use:

$0.4 \le \beta \le 0.75 \qquad 0 < X_{LM} \le 0.3$

$Fr_{gas,th} > 3 \qquad DR > 0.02$

Stated Uncertainties:

Uncertainty of gas flow rate prediction for $X_{LM} \le 0.15$ is 3%
Uncertainty of gas flow rate prediction for $X_{LM} > 0.15$ is 2.5%

$$H = 1 + 0.35WLR_m \tag{13}$$

ISO TR 11583 states the applicable limits of the wet gas Venturi meter $OR=f(X_{LM})$ correlation. These limits are stated in Table 1 along with the Tek-Trol DP Flow Solutions (TDFS) massed data set range. The TDFS data set (as with other select confidential manufacturer data sets) has wider parameter ranges than the ISO correlation, notably the inclusion of lower $Fr_{g,th}$ and *DR* values, some higher Fr_g/H values, and gas with liquid hydrocarbon *and* water wet gas flows. Van Putten [7] shows some data with such extrapolation of the ISO TR 11583 correlation. This present data set shows further extrapolated data.

TDFS has wet gas flow data from 35 separate Venturi meters, all with downstream pressure taps. Figs 2 thru 12 show sample photographs of some of these meters under test. There are single data sets from the TUVNEL and DNV wet gas test facilities, with most data from the CEESI wet gas test facility. There was 1935 wet gas points (i.e. $X_{LM}>0$) with primary DPs>2.5 kPa (i.e. >10"WC). To avoid any potential low DP high uncertainty issues, all data with primary DPs <2.5 kPa were excluded from the analysis. Of these 1935 useable data points 1311 points were entirely inside the ISO TR 11583 $OR = f(X_{LM})$ range, with 1244 being gas with liquid hydrocarbon flows and 67 points being gas with water flows. Of the data with parameters outside the ISO correlation there are 409 points with gas with liquid hydrocarbon *and* water flow, 62 points with $2<Fr_{g,th}<3$, 127 points with 0.01<DR<0.02, and 26 points with both $2<Fr_{g,th}<3$ and 0.01<DR<0.02. This low density ratio coupled with low throat gas densiometric Froude number data has a mix of gas with liquid hydrocarbon and / or water flow.

Figs 13 and 14 reproduce results from van Putten [7] and Reader Harris [4]. They show that the ISO TR 11583 wet gas Venturi meter $OR\%=f(X_{LM})$ correlation tends to correctly predict the gas mass flowrate for a given Lockhart Martinelli parameter. However, a slight negative bias is evident at higher Lockhart Martinelli parameters. Reader Harris [4] shows that wet gas flows that include water (i.e. '3-phase' flow) tend to have this slight negative bias, but there is also some negative bias for gas with liquid hydrocarbon only (i.e. '2-phase') data.

Fig 2. 4”, 0.4β Meter at CEESI

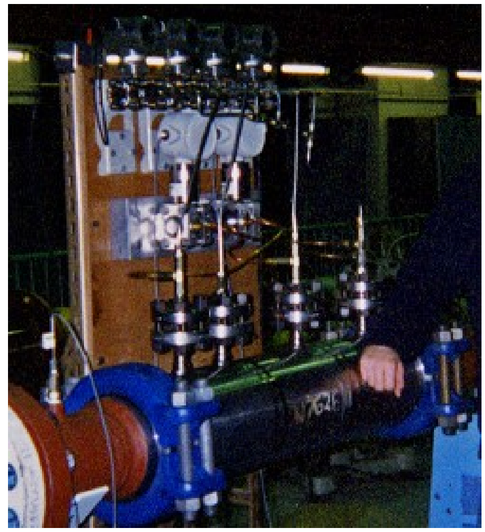


Fig 3. 6”, 0.55β Meter at TUVNEL.

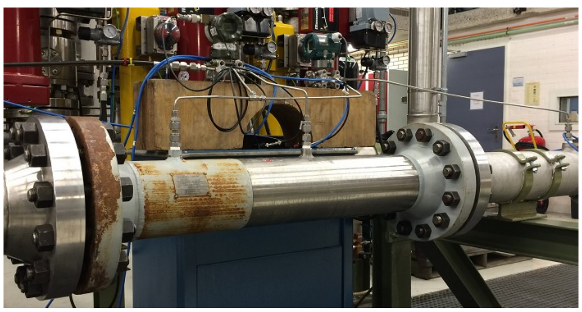


Fig 4. 6”, sch 80, 0.6β at DNV.

Fig 5. 8”, sch 80, 0.6β at CEESI.

Fig 6. (Left to Right) 4”, 0.6β, 0.75β, and 0.75β Meters at CEESI.

Fig 7. 6″, 0.55β at CEESI.

Fig 8. 6″, 0.6β at CEESI.

Fig 9. 2″, 0.6β at CEESI.

Fig 10. 8″, 0.6β at CEESI.

Fig 11. 6″, 0.7β Meter at CEESI

Fig 12. 6″, 0.6β Meter at CEESI

Figure 15 shows all the TDFS wet gas data within the parameter range of ISO TR 11583 OR=f(X_{LM}) corrected for a known liquid flowrate. For the gas and liquid hydrocarbon flow (i.e. WLR_m=0) H=1 was used. For gas and liquid hydrocarbon flow there are far more data points at $X_{LM} \leq 0.15$ than $X_{LM} > 0.15$. Data at $X_{LM} > 0.15$ tends to have a slight negative bias, including some negative outliers.

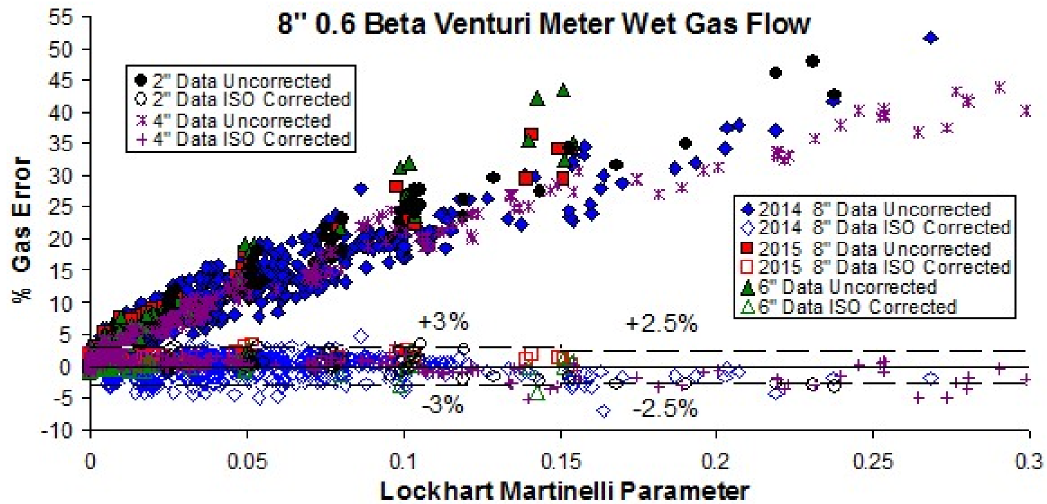


Fig 13. Four Wet Gas Venturi Meter Data Sets Shown by van Putten et al [7].

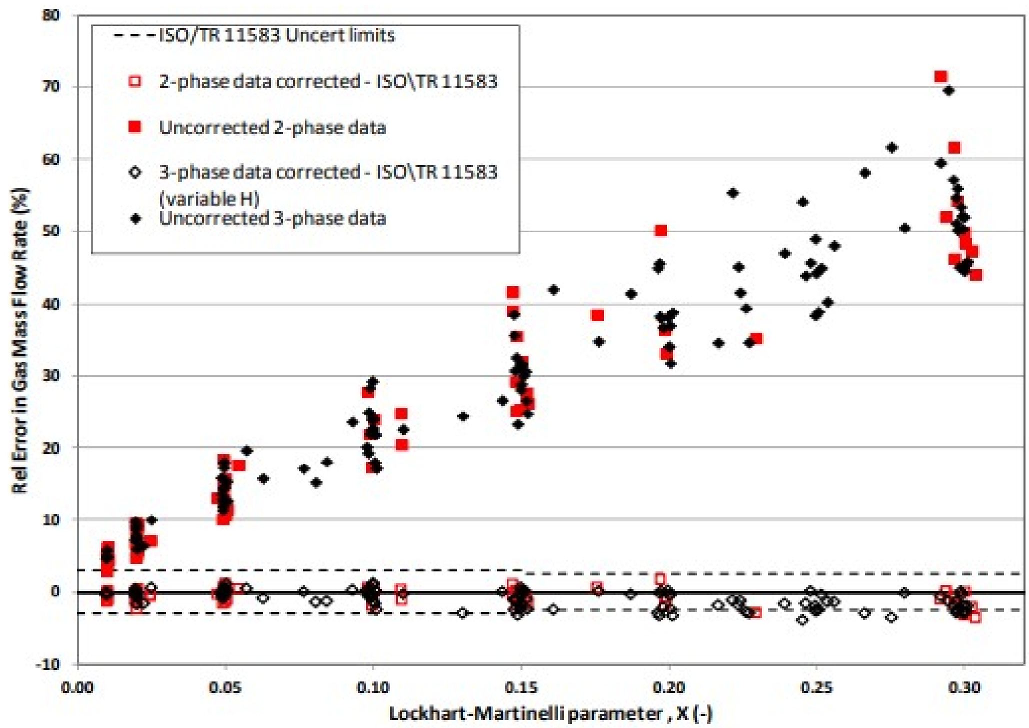


Fig 14. Wet Gas Venturi Meter Data Shown by Reader Harris [4].

Nevertheless, of the 1244 gas with liquid hydrocarbon wet gas points the ISO OR=f(X_{LM}) correlation fits the data to 2.5% at 95% confidence. For the gas and water flow (i.e. $WLR_m=1$) H=1.35 was used. The gas and water wet gas flow data is limited to $X_{LM}\leq0.17$. Of the 67 gas with water wet gas points the ISO OR=f(X_{LM}) correlation fits the data to 3.1% at 95% confidence. A general trend in the ISO TR 11583 Venturi meter wet gas OR=f(X_{LM}) correlation check is that the original stated uncertainty of 3% for $X_{LM}\leq0.15$ and 2.5% for $X_{LM}>0.15$ would be better set to 3% uncertainty across the $0<X_{LM}\leq0.3$ range. But, in general the ISO correlation does well.

Figure 16 adds the 409 wet gas flow data points for where there is multiphase wet gas data (i.e. $0<WLR_m<1$) but all other parameters within the ISO TR 11583 correlation range. For a known total liquid flowrate, when extrapolating the ISO Venturi meter wet gas OR=f(X_{LM}) correlation for use with $0\leq WLR_m\leq1$, and

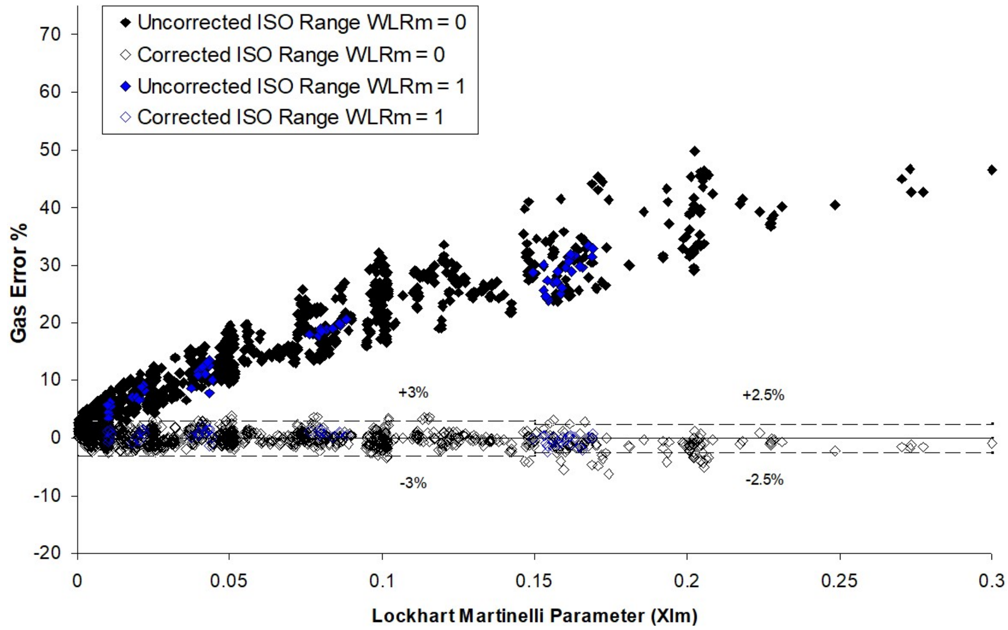


Fig 15. All Data within ISO TR 11583 Parameter Range.

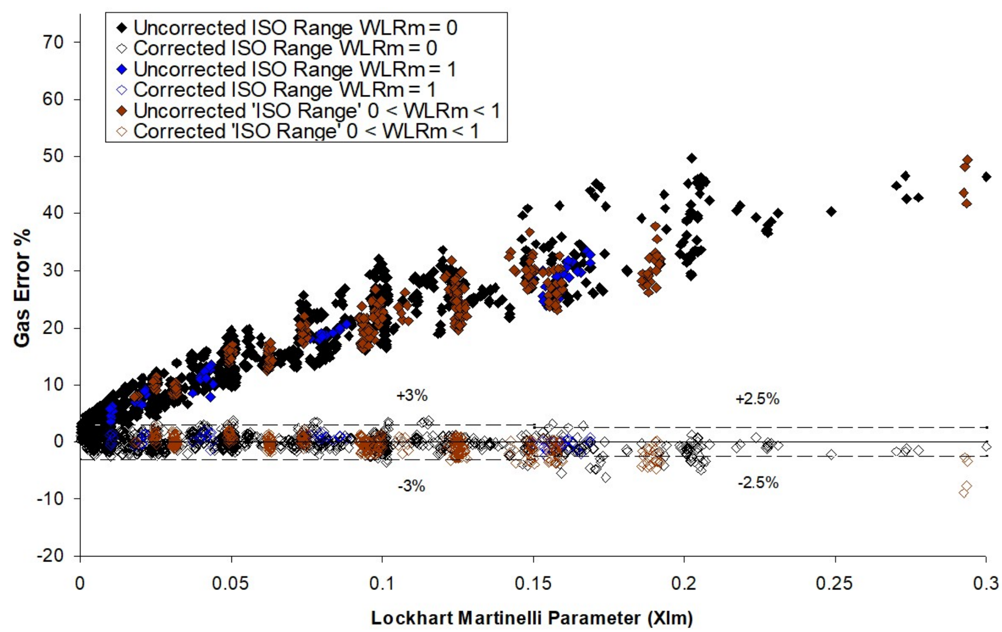


Fig 16. All Data Within the ISO TR 11583 Range and Multiphase Wet Gas Flow Where All Other Parameters are Within ISO TR 11583

assuming a linear relationship between WLR_m and the parameter H, i.e. equation 13, the gas flow is predicted to 3.3% at 95%.

Figure 17 shows all 409 points with $0 \le WLR_m \le 1$ data that has all other parameters within the ISO TR11583 wet gas Venturi meter correlation, and the addition of:

1) Sixty two wet gas points with low throat gas densiometric Froude no. data, i.e. $2 < Fr_{g,th} < 3$. The ISO $OR = f(X_{LM})$ correlation predicts the gas flow to 3% at 95% confidence.

2) One hundred and twenty seven wet gas points with low gas to liquid density ratio data, i.e. 0.01<DR<0.02. The ISO $OR=f(X_{LM})$ correlation predicts gas flow to 5.5% at 95% confidence.

3) Twenty six wet gas points with a combination of low throat gas densiometric Froude number and low gas to liquid density ratio, i.e. $Fr_g<3$ and $DR<0.02$. The ISO $OR=f(X_{LM})$ correlation predicts the gas flow to 3.5% at 95% confidence.

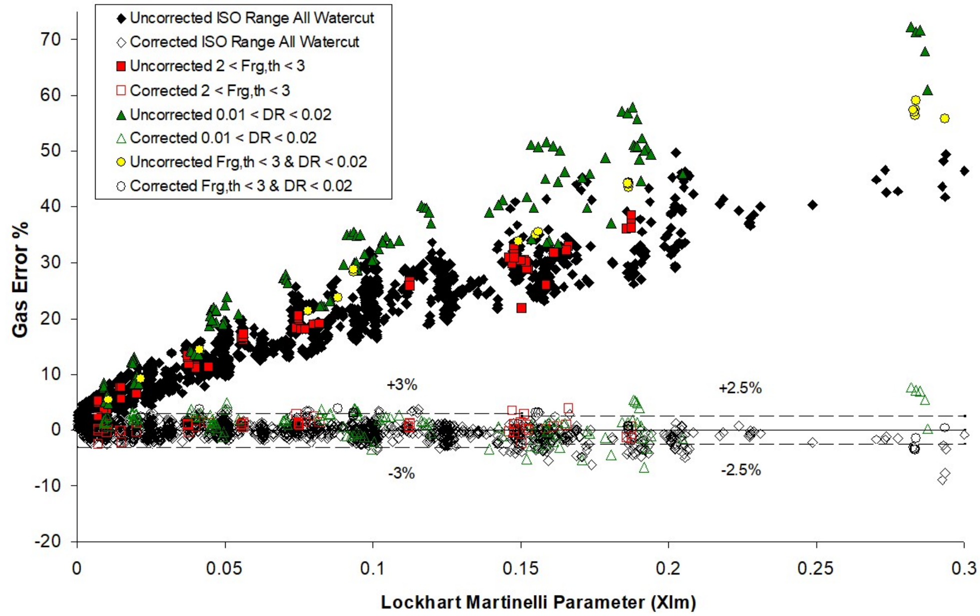


Fig 17. All Gas with Liquid Hydrocarbon and / or Water Data With Parameters Inside ISO Parameter Ranges, Plus Low $Fr_{g,th}$, Low DR, & Combination of Low $Fr_{g,th}$ / Low DR Data.

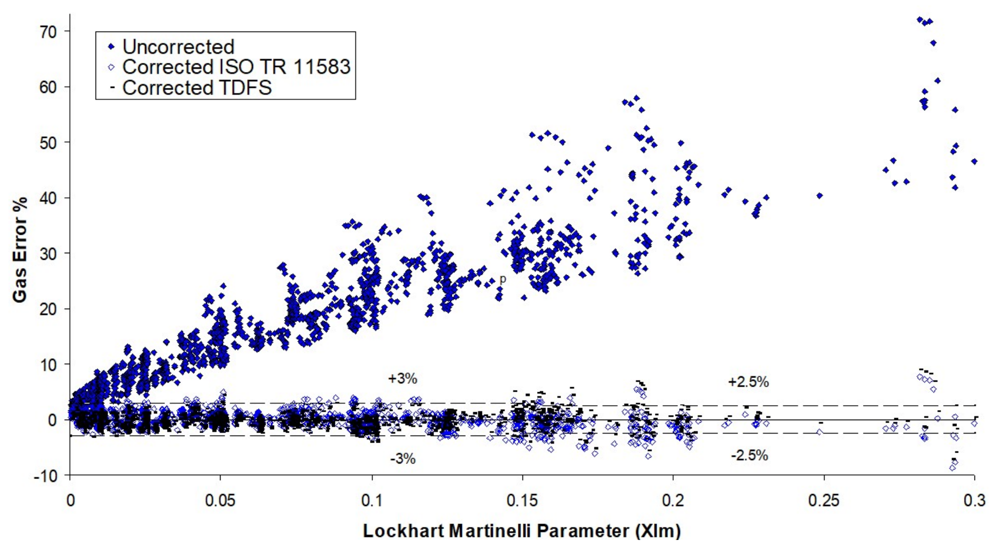


Fig 18. All Gas with Liquid Hydrocarbon and / or Water Data With an ISO TR 11583 Correction and an Alternative Commercial TDFS Correlation.

Extrapolating the limits of the ISO Venturi meter $OR=f(X_{LM})$ correlation to the lower throat gas densiometric Froude number had little adverse effect. Extrapolating the limits to the lower density ratio had a noticeable effect, increasing the gas flow prediction uncertainty to 5.5%. The spread was a scatter rather than any obvious bias.

Figure 18 shows all the available wet gas data. For the test data range (see Table 1) with a known WLR_m and known total liquid flowrate the ISO $OR=f(X_{LM})$ correlation predicts the gas flow to 3.1% at 95% confidence. However, in truth the correlation performs better at $X_{LM} < 0.15$, and data at $DR < 0.02$ has a larger uncertainty of 5.5% at 95% confidence.

These results generally agree with the findings of Collins et al [5], Steven et al [6], van Putten et al [7], and Bjorner M et al [8]. Furthermore, Collins and Bjoner discuss the possibility of updated and / or commercial wet gas correlaions. Various wet gas Venturi meter manufacturers offer their own confidential wet gas correlations embedded in wet gas Venturi meter product firmwares. Using more data at wider flow parameter ranges and/or specific meter geometries, these commercial correlations can have lower uncertainty than the general ISO public correlation.

For example, TDFS has developed such a wet gas Venturi meter $OR=f(X_{LM},DR,Fr_g,WLR_m)$ correlation. Figure 18 shows the result of applying the TDFS confidential correlation gas mass flow prediction for a known WLR_m and total mass flowrate across the full parameter test range. This correlation example predicts the gas flowrate to 2.5% at 95% confidence, i.e. a modest improvement on the ISO 3.1% at 95% confidence.

4 HORIZONTAL VENTURI METER X_{LM}=f(PLR) CORRELATIONS

The availability of a wet gas Venturi meter $OR = f(X_{LM})$ correlation is academic if the user doesn't know the wet gas flow's liquid loading, i.e. Lockhart Martinelli parameter X_{LM}. To meter the gas flow it is first necessary to know or predict the Lockhart Martinelli parameter.

4.1 ISO TR 11583 VENTURI METER X_{LM}=f(PLR) CORRELATION CHECK

ISO TR 11583 offers wet gas Venturi meter $X_{LM} = f(PLR)$ correlation, where the Pressure Loss Ratio (*PLR*) is defined as the ratio of the permanent pressure loss (ΔP_{PPL}) to the primary DP (ΔP_t), i.e. $PLR = \Delta P_{PPL}/\Delta P_t$ (see Fig 1). The permanent pressure loss is read between the inlet port and a pressure port located 6D downstream of the meter's diverging 'diffuser' section. This ISO $X_{LM}=f(PLR)$ correlation is shown here as equation set 14 thru 16.

$$Y = PLR - 0.0896 - 0.48\beta^9 \tag{14}$$

$$Y_{\max} = 0.61\exp\left\{-11\left(\frac{\rho_g}{\rho_l}\right) - 0.045\left(\frac{Fr_g}{H}\right)\right\} \tag{15}$$

$$X_{LM,pred} = \left(\frac{-1}{35}\left(\frac{\ln\left(1-\frac{Y}{Y_{\max}}\right)}{\exp\left(-0.28\frac{Fr_g}{H}\right)}\right)\right)^{4/3} \tag{16}$$

The limits of this equation are described as:

If Y/Ymax > 0.7 'it is not possible' to use the pressure-loss ratio to determine X_{LM}.
If Y/Ymax < 0.7 X_{LM} is evaluated from Equation 8.

Additional ISO Parameter limitations are:

$Fr_{gas,th} > 4$ $\quad$ $Fr_g / H < 5.5$ $\quad$ $DR < 0.09$

Stated Uncertainties:

Uncertainty of gas flow rate prediction for derived X_{LM} is stated as 5%

Although the limits of the ISO $X_{LM} = f(PLR)$ correlation are technically stated they are in practice obscure. What is the maximum Lockhart Martinelli parameter that can be predicted? There is no direct statement. It turns out that '*it depends*'. It depends on the *Y/Ymax* value found in service. And that depends on the two variables that aren't known until the meter is in service, i.e. the *PLR* and the gas densiometric Froude number. (For known fluids at a given thermodynamic condition the gas to liquid density ratio and the parameter H are known.)

Hence, an operator has no assurance that this ISO Lockhart Martinelli parameter method is guaranteed to work across any stated Lockhart Martinelli parameter range on any particular application. The result depends on various meter performance and flow condition parameters, some of which are only known once the meter is in service.

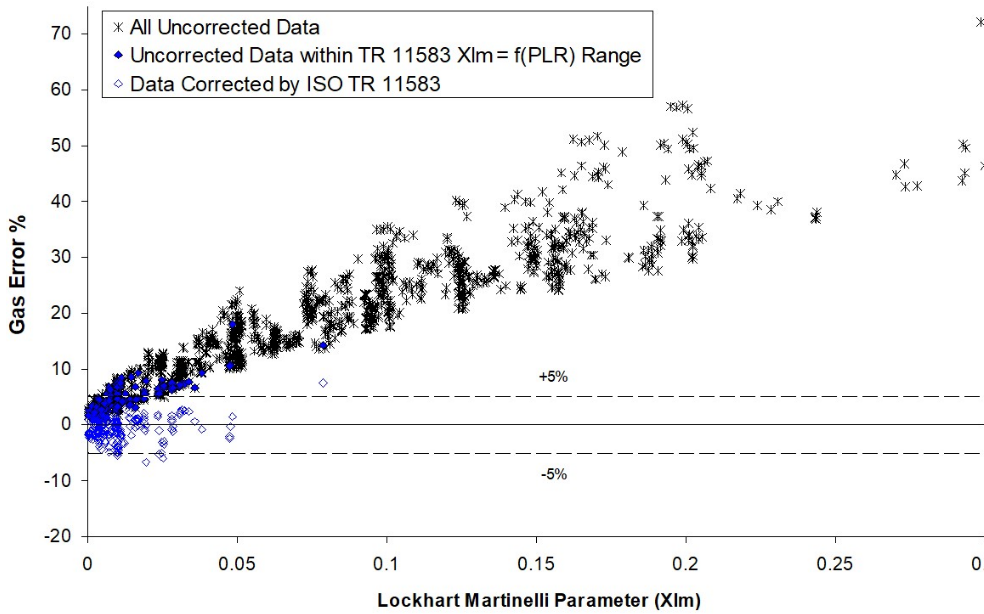


Fig 19. All Uncorrected Wet Gas Venturi Data and the Corrected Data (with ΔP_{PPL} > 20"WC) for When ISO $X_{LM} = f(PLR)$ Was Within its Range.

Figure 19 shows massed data from thirty four[1] wet gas Venturi meters. The uncorrected over-reading (*OR%*) vs. reference Lockhart Martinelli parameter (X_{LM}), and the corresponding corrected data for those points that produce results within the ISO $X_{LM}=f(PLR)$ prediction range are shown. Much of this massed data was logged with permanent pressure loss (ΔP_{PPL}) DP transmitters with upper range limits of 400"WC or 250"WC. Hence, all ΔP_{PPL}<20"WC has been removed to avoid higher uncertainty values being used in the analysis.

In order to use the ISO TR 11583 $X_{LM}=f(PLR)$ prediction method with confidence for a given Lockhart Martinelli parameter range an operator needs a reasonable guarantee that the method will work across the range required. ISO TR 11583 doesn't offer that guarantee. In service, if it is found that $Y/Y_{max} \leq 0.7$ then a result is obtained. However, if it transpires that $0.7 < Y/Y_{max} < 1$, then this is outside the correlation range, and the ISO $X_{LM}=f(PLR)$ correlation can give an erroneous Lockhart Martinelli prediction result. These erroneous results are not shown in Figure 19. If $Y/Y_{max} \geq 1$ then the ISO correlation gives no result. Furthermore, the maximum Lockhart Martinelli parameter that can be reliably predicted varies with the PLR read and the flow conditions.

Figure 20 shows the thirty four meter combined data set for $X_{LM} \leq 0.06$ within the ISO TR 11583 correlations parameter range. Even at this low range many of the wet gas flow conditions do not produce $Y/Y_{max} \leq 0.7$ and therefore have no associated ISO $X_{LM} = f(PLR)$ Lockhart Martinelli parameter result.

[1] The thirty fifth Venturi meter in this massed data set had the downstream tap in a significantly different location to 6D downstream of the diffuser and is therefore not included in this analysis.

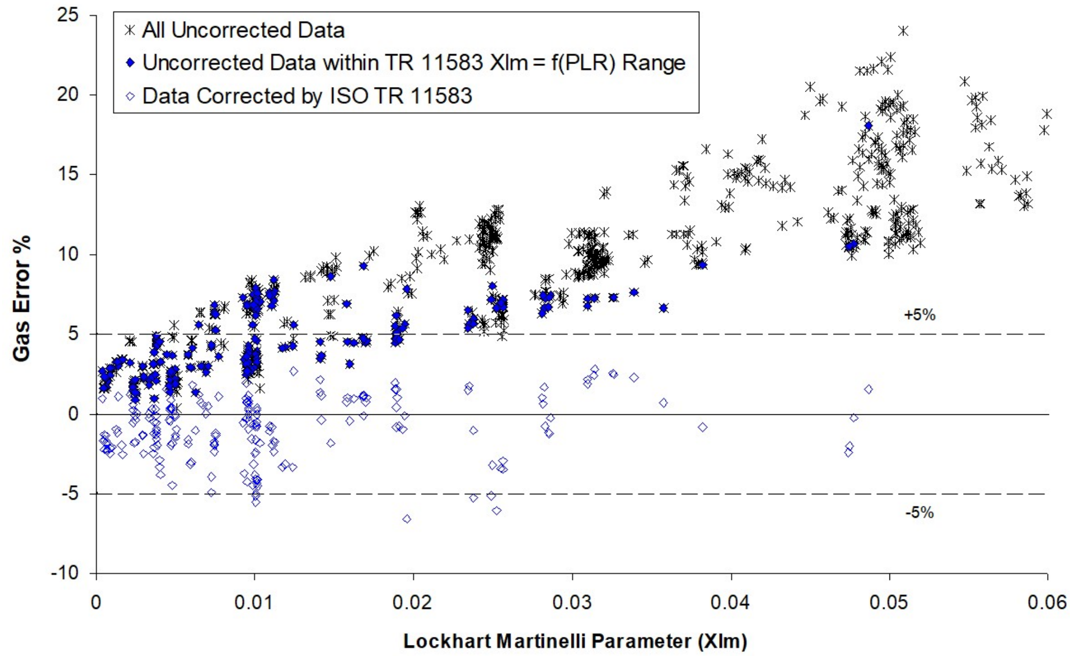


Fig 20. All Uncorrected Wet Gas Venturi Data and the Corrected Data (with ΔP_{PPL} > 20”WC)for When ISO $X_{LM} = f(PLR)$ Was Within its Range, for X_{LM} < 0.06.

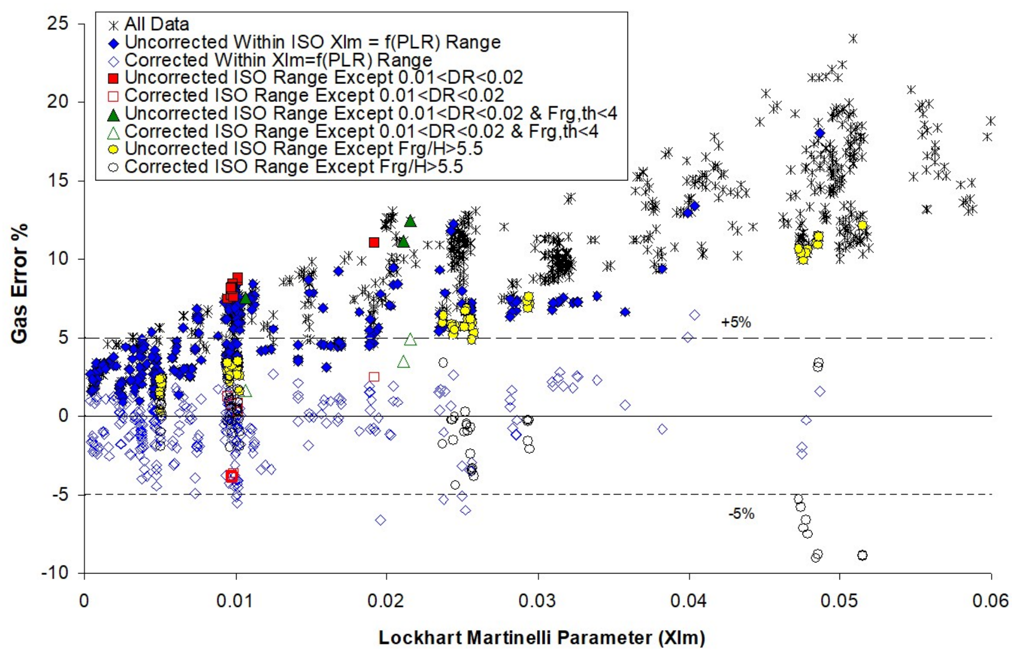


Fig 21. Uncorrected Wet Gas Venturi Data and the Corrected Data for When ISO’s X_{LM} = f(PLR) Gave a Valid Result, for X_{LM} < 0.06

Figure 21 shows the massed data set X_{LM} < 0.06 points where the ISO TR 11583 correlation parameter range has been increased to include $Fr_{g,th}$>2, DR>0.01, or Fr_g/H> 8 points, and combinations of these extrapolations. This additional data has gas with hydrocarbon, or gas with water. In general, the ISO correlation worked at these extrapolated ranges, i.e. if for $Y/Y_{max} \leq 0.7$ the method produces a Lockhart Martinelli parameter prediction generally in the same uncertainty range as the data within the ISO TR 11583 range. A notable exception was data with X_{LM}>0.047, DR>0.082 (i.e.>75 Bar) and Fr_g/H>7 (i.e. >22 m/s). These flow point, almost certainly with annular mist flow, tended to have their gas flowrate over-corrected, i.e. too much liquid and too little gas is predicted.

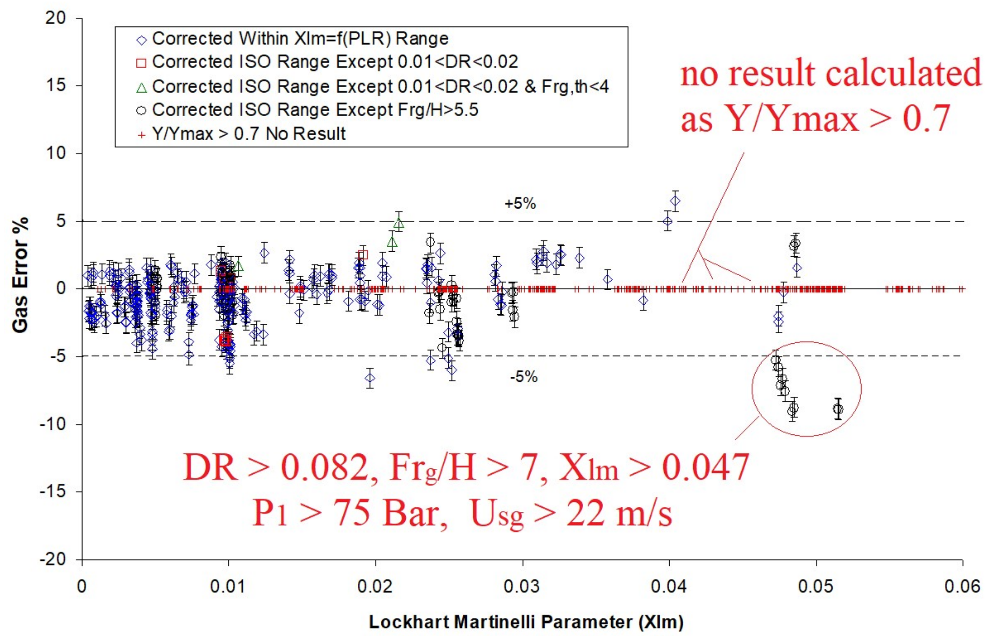


Fig 22. All Data (with ΔP_{PPL} > 20"WC)
With Lockhart Martinelli Parameter Predictions and the No Results Cases.

Figure 22 shows all 34 Venturi meter massed data set $X_{LM}<0.06$ points with all applicable ($Y/Y_{max}\leq0.7$) ISO TR 11583 corrected data results. There are many points at $X_{LM}\leq0.06$ for which the result gives $Y/Y_{max}>0.7$ and therefore no valid ISO Lockhart Martinelli parameter prediction result. Such 'no result' points are shown as a red cross on the x-axis.

It is not practical for an operator to use a method of wet gas metering that may or may not give a result in service. Therefore, does this result exclude the Venturi meter $X_{LM} = f(PLR)$ method from practical industrial use? Or is this result more due to limited data sets used in the ISO analysis, coupled with the typical very conservative approach of ISO?

4.2 Commerical Venturi Meter X_{LM} =f(PLR) Correlations

Figure 23 shows all the 34 Venturi meter $X_{LM}<0.06$ massed data set X_{LM} vs *PLR* points. First glance suggests that there is a general X_{LM} vs *PLR* trend where increasing Lockhart Martinelli parameter (X_{LM}) produces an increasing PLR. But Figure 23 also shows a lot of scatter. However, much of this perceived scatter is due to predictable beta (β), gas to liquid density ratio (*DR*), and gas densiometric Froude number (Fr_g) effects.

Figure 24 shows the massed data set with data from one meter, an 8", 0.6β Venturi meter, showing two distinct gas to liquid density ratios. Figure 25 highlights this meter's distinct gas densiometric Froude number groups at a set gas to liquid density ratio. These results are typical throughout the 34 Venturi meter data sets. Hence, with a massed data set it is possible to extend the published ISO $X_{LM}=f(PLR)$ fit such that the resulting correlation guarantees a Lockhart Martinelli parameter prediction up to some maximum Lockhart Martinelli parameter value.

Indeed, this has arguably been done by some flow meter manufacturers that offer sophisticated commercial wet gas Venturi meter designs, where the Venturi meter $X_{LM}=f(PLR)$ method is one of several methodologies used in a larger more complex system. However, there is little in the literature about practically using the standalone $X_{LM}=f(PLR)$ method with a standard horizontally installed Venturi meter in a low to moderate liquid loading wet gas applications.

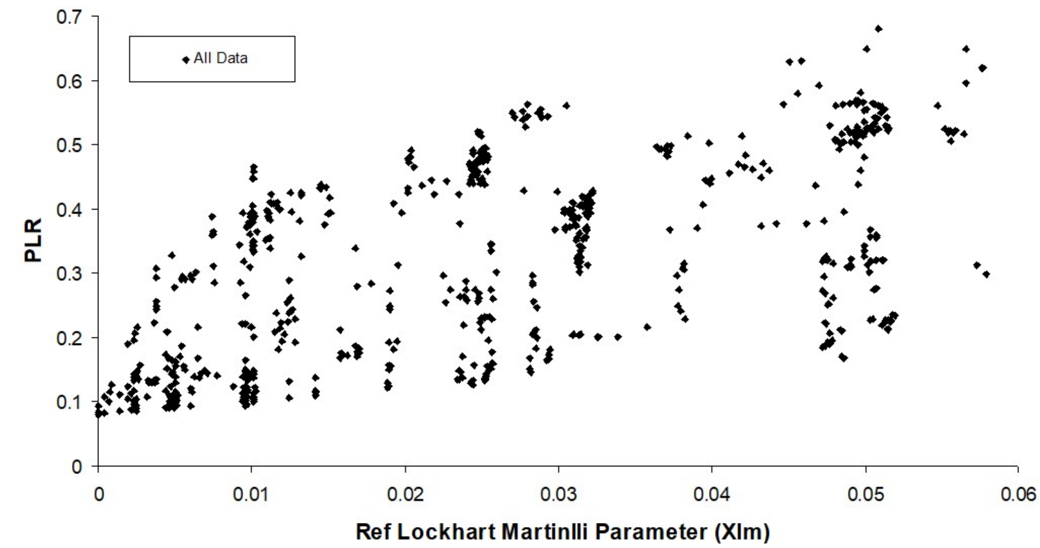


Fig 23. All 34 Venturi Meter X_{LM} vs. PLR Data for X_{LM} < 0.06.

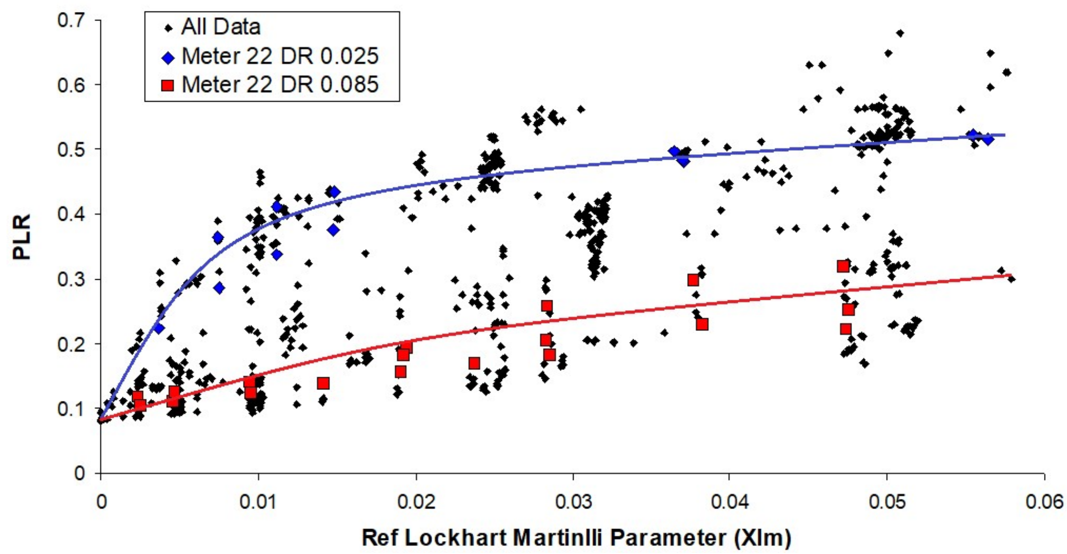


Fig 24. All X_{LM} vs. PLR Data with an 8", 0.6β Meter's Density Ratio Data Highlighted.

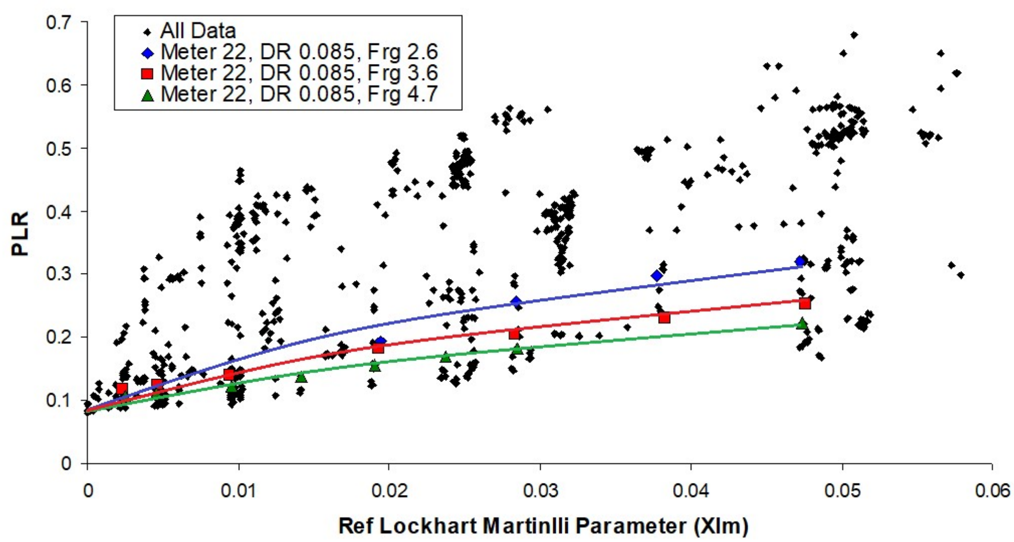


Fig 25. All X_{LM} vs. PLR Data with an 8", 0.6β Meter's Fr_g Data at Constant DR Highlighted.

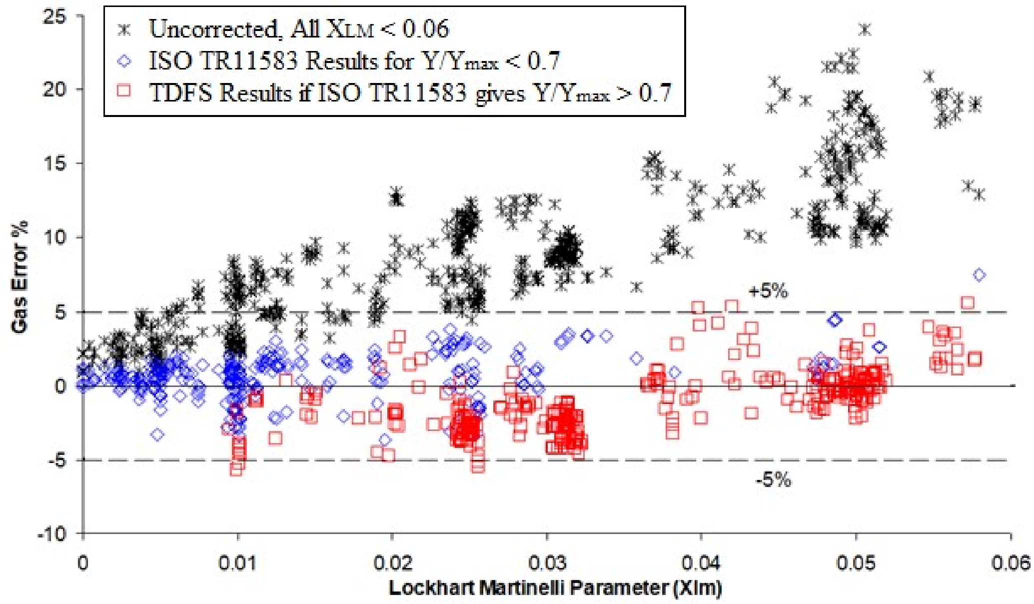


Fig 26. All X_{LM}<0.06 Uncorrected Wet Gas Venturi Data and Data Corrected by ISO $X_{LM}=f(PLR)$ for $Y/Y_{max}\leq0.7$ and TDFS $X_{LM}=f(PLR)$ for $Y/Y_{max}>0.7$.

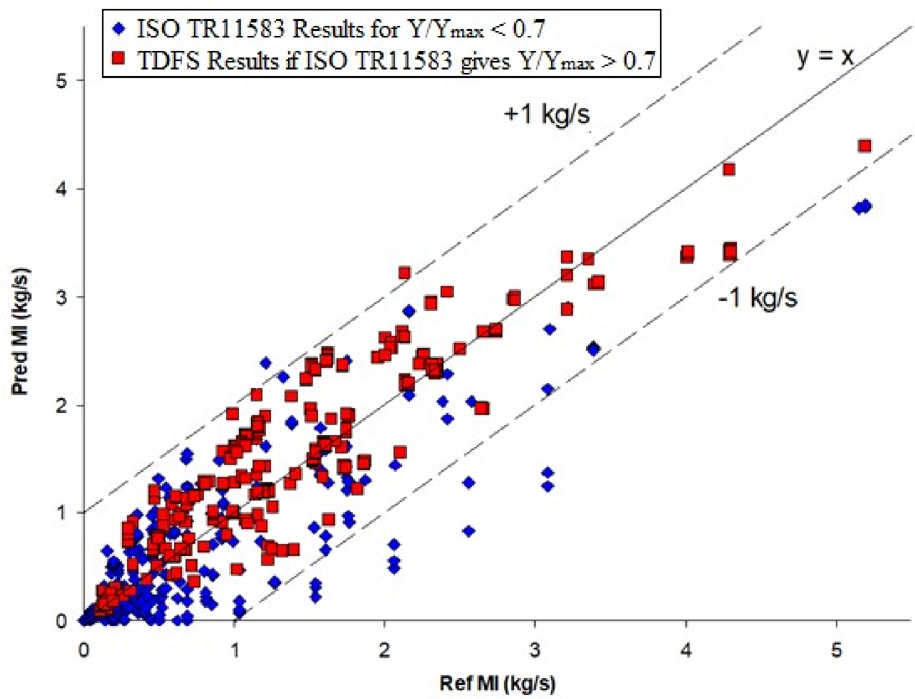


Fig 27. All X_{LM}<0.06 Wet Gas Venturi Data Liquid Mass Flowrate Predictions Using ISO $X_{LM}=f(PLR)$ for $Y/Y_{max}\leq0.7$ and TDFS $X_{LM}=f(PLR)$ for $Y/Y_{max}>0.7$

As way of example, based on these 34 wet gas Venturi meter data sets, TDFS has produced a confidential wet gas Venturi meter $X_{LM}=f(PLR,DR,Fr_g,\beta)$ correlation for X_{LM}<0.06. Figure 26 shows the results of applying this correlation. All 34 Venturi meters uncorrected data (with with ΔP_{PPL}>20"WC) are shown, along with the ISO correction for $Y/Y_{max}\leq0.7$, and the TDFS correction for when the ISO correlation is not appicale due to a $Y/Y_{max}>0.7$ result. The gas mass flowrate is corrected to 4.2% at 95% confidence.

Once the Lockhart Martinelli parameter is found, allowing the gas mass flowrate to be estimated, for the known gas to liquid density an associated liquid mass flowrate prediction is found, $m_l=f(m_g,X_{LM},DR)$. Figure 27 shows the associated result of the liquid mass flowrate prediction for both ISO's $Y/Y_{max} \leq 0.7$ results and TDFS's correlation results when ISO's correlation produces $Y/Y_{max} > 0.7$. As with most wet gas meters the liquid flowrate prediction is best effort, and not usually a prediction that comes with an associated uncertainty statement. As the Lockhart Martinelli parameter tends to zero it naturally becomes more difficult to meter the liquid at a low percentage. Hence, the liquid mass flow prediction is presented here in absolute terms.

4.3 Unknown Water to Liquid Mass Ratio

In some applications the operator will not have precise knowledge of the water liquid mass ratio (WLR_m). In such cases the liquid density ($\rho_{l,hom}$), gas to liquid density (DR), gas densiometric Froude number (Fr_g), and in the case of the ISO correlation the parameter H, are not precisiely known. Fortunately, wet gas Venturi meter correlations are *relatively* insensitive to the Water Liquid Mass Ratio (WLR_m). Figure 28 shows the effect of assuming the massed data is all liquid hydrocarbon (i.e. WLR_m=0), or an even split of liquid hydrocarbon and water (i.e. WLR_m=1/2), or all water (i.e. WLR_m=1). There is only a marginal reduction in the wet gas correlation performance by estimating (or guessing) the liquid water mass ratio.

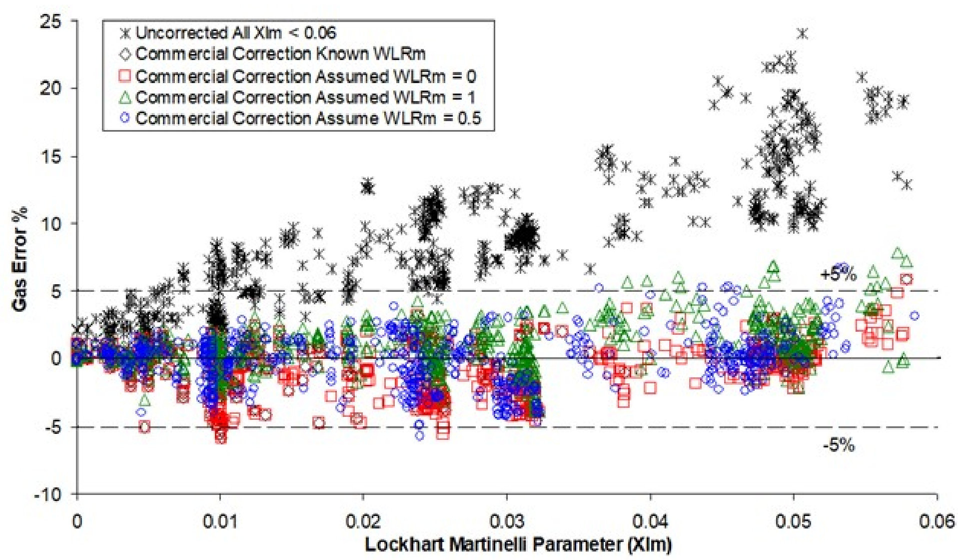


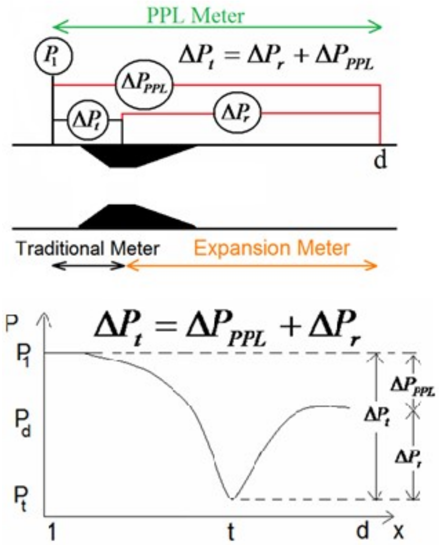
Fig 28. Commercial Correlation Example When WLR_m Not Known.

4.4. Wet Gas Venturi Meter Diagnostics

The Venturi meter shown in Fig.1 shows a sketch of a wet gas Venturi meter with the de Leeuw arrangement of two DP transmitters reading the permanent pressure loss (ΔP_{PPL}) and primary DP (ΔP_t) from three pressure ports, *specifically* to monitor and track wet gas flow. An inherent assumption with this traditional methodology, as practiced by several wet gas Venturi meter designs, is that ***any*** shift seen in the Pressure Loss Ratio (PLR), i.e. PLR = $\Delta P_{PPL}/\Delta P_t$, ***must*** singularly be due to a change in the Lockhart Martinelli parameter.

In reality this is not necessarily true. Many issues can cause a Venturi meter's read PLR to change, e.g. a drifting or saturated DP transmitter, a plugged impulse line, meter erosion or contamination, the appearance of an inlet flow disturbance, a partial blockage etc. Such blind assumption that a PLR shift is due to liquid loading change is metering on hope and faith. However, modern wet gas Venturi meter operators do not have to blindly assume a shift in PLR is due to wet gas flow. This can be verified by use of the modern Venturi (and general DP) meter axial pressure profile analysis diagnostic system (called 'Prognosis').

Prognosis' uses a third DP reading, i.e. the recovered DP (see dashed lines superimposed on Fig. 1). This allows the Venturi meter's axial pressure profile to be analysed. Different meter problems cause different changes to the meter's axial pressure profile. Figure 29 shows an overview of the Prognosis system.



- DP Integrity Check:

  $\Delta P_t = \Delta P_r + \Delta P_{PPL}$

- Three Flowrate Predictions to Compare:

  Primary Flow Equation: $m_t = f(\Delta P_t)$

  Expansion Flow Equation: $m_r = f(\Delta P_r)$

  PPL Flow Equation: $m_{PPL} = f(\Delta P_{PPL})$

- Three DP Ratios Compared Against Calibrated Gas Flow Baseline:

  $PLR = \Delta P_{PPL} / \Delta P_t$

  $PRR = \Delta P_r / \Delta P_t$

  $RPR = \Delta P_r / \Delta P_{PPL}$

- DP and Parameter Stability Checks

Fig 29. Venturi Meter Prognosis Diagnostic / Verification System Overview.

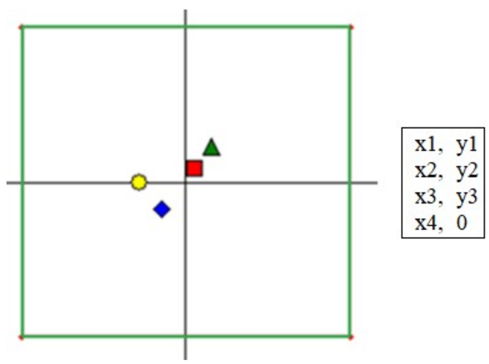


Fig 30. Typical Single Phase Gas Venturi Meter Prognosis Result.

The Prognosis axial pressure profile analysis results are usually plotted in a simple display such that an entry level technician understands if there is a problem. Seven diagnostic checks consisting of the DP check, the three flowrate comparisons, and the three read to baseline DP ratio comparisons, are plotted as four points (with seven co-ordinates) on a graph (see Fig 30). A correctly operating single phase Venturi meter has these points inside a green box.

A Venturi meter that does not behave as a single phase flow correctly operating meter produces one or more points outside the box. Figure 31 shows three such examples, where three different meter issues cause three different Prognosis patterns. All three examples chosen are for issues that cause the read PLR to increase. In the standard wet gas Venturi meter methodology any increase in PLR is blindly assumed to be due to an increase in wet gas liquid loading.

The left side Figure 31 example shows the case of a primary DP transmitter reading with a negative drift. This produces a PLR increase. Unlike the standard method Prognosis shows this is NOT wet gas flow and knows not to calculate an associated Lockhart Martinelli parameter. The middle Figure 33 example shows the case where the Prognosis pattern recognition identifies the cause as one of an incorrect geometry use, a partial throat blockage, disturbed flow, or contaminated flow, but NOT wet gas flow. Again, there is an increase in PLR, but unlike the standard method Prognosis knows not to calculate an associated Lockhart Martinelli parameter. The right side Figure 31 example shows the case of wet gas flow. This produces an increase in PLR. Whereas an average pattern over time looks like the pattern caused by an incorrect geometry use, a partial throat blockage, disturbed flow, or contaminated flow, it is the coupling of this result with the turbulence diagnostics that specifically identifies wet gas flow. Wet gas flow is relatively unsteady, induces high frequency short period signal fluctuations, and this manifests itself with a very variable Prognosis plot.

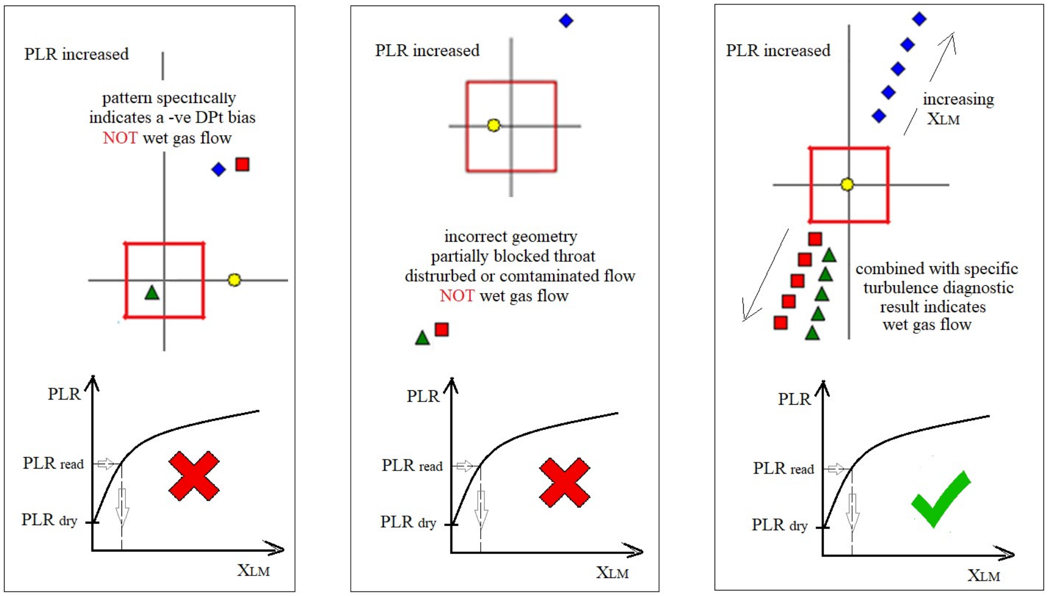


Fig 31. Examples of Different Venturi Meter Problems Causing Increase in PLR and Prognosis pattern recognition.

Figure 32 reproduces a graph from Rabone et al [9] showing the Prognosis turbulence differentiation between a wet gas flow, a plugged impulse line, and a correctly operating meter. This example shows the general principle, although real data is considerably more chaotic. Therefore, unlike the standard method, Prognosis first verifies the issue ***is*** wet gas flow ***before*** it then uses the $X_{LM}=f(PLR)$ relationship to predict the Lockhart Martinelli parameter.

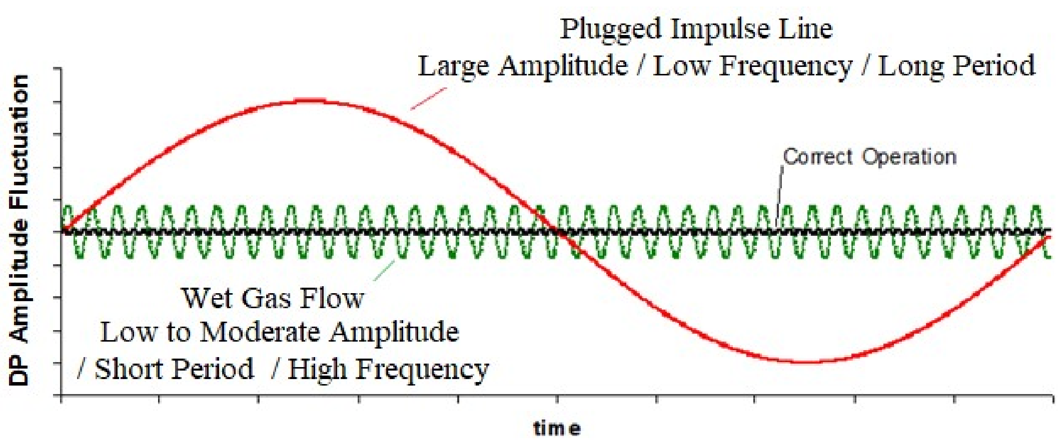


Fig 32. Venturi Meter DP Fluctuations Differences Between Single Phase Correct Gas Flow Operation, a Plugged Impulse Line, and Wet Gas Flow.

4.5 Three DP Transmitter Assembly Provides DP Reading Redundancy

Wet gas flow is an extremely adverse flow condition for DP transmitters.

Wet gas flow is rarely truly steady, and industrial flows said to be steady are usually only pseudo-steady, i.e. their values fluctuate significantly around a repeatable mean (e.g. see Fig 32). Furthermore, wet gas flow often includes periodic slugging flow, which causes sudden large spikes in DPs. Such periodic spiking and rapid signal fluctuation can cause DP transmitters to prematurely drift giving positive or negative biased DP readings.

Wet gas flows that include water can cause hydrate plugs in impulse lines. A plugged impulse line will adversely affect any DP transmitter it is connected to. A DP transmitter with a plugged impulse line will, for a relatively steady flow, tend to produce a DP signal with a long period high amplitude fluctuation around the correct answer, caused by the natural small line pressure fluctuation. The DP therefore has a cyclic significant positive bias followed by a significant negative bias.

Wet gas flow tends to cause significantly higher DPs than would be produced if the gas flowed alone. With wet gas flow often not expected, and with few trained to predict wet gas flow DP ranges even if it is expected, it is common for DP meters in wet gas flow applications to have saturated (i.e. over-ranged) DP transmitters. A saturated DP transmitter reads a DP with a negative bias.

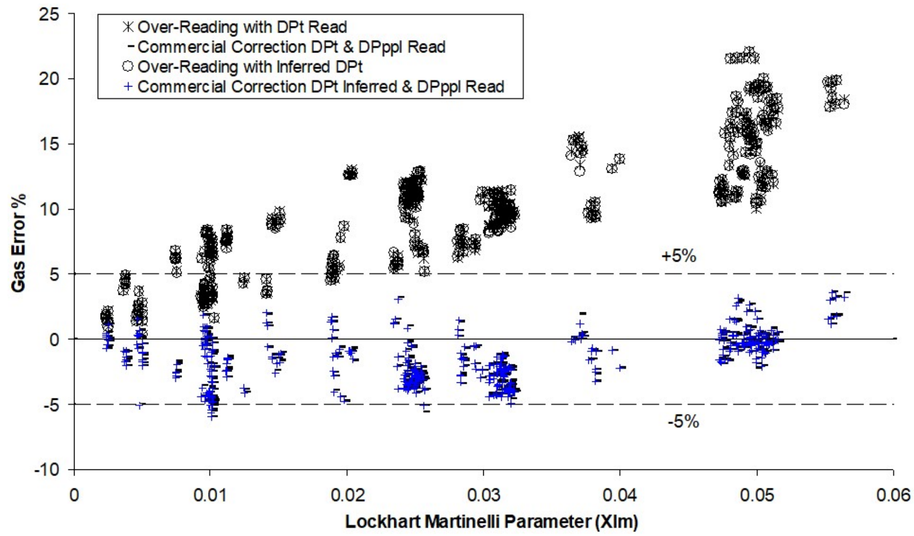


Fig 33. Wet Gas Venturi Meter Correlation Applied to Massed Data With Inferred Primary DP_t.

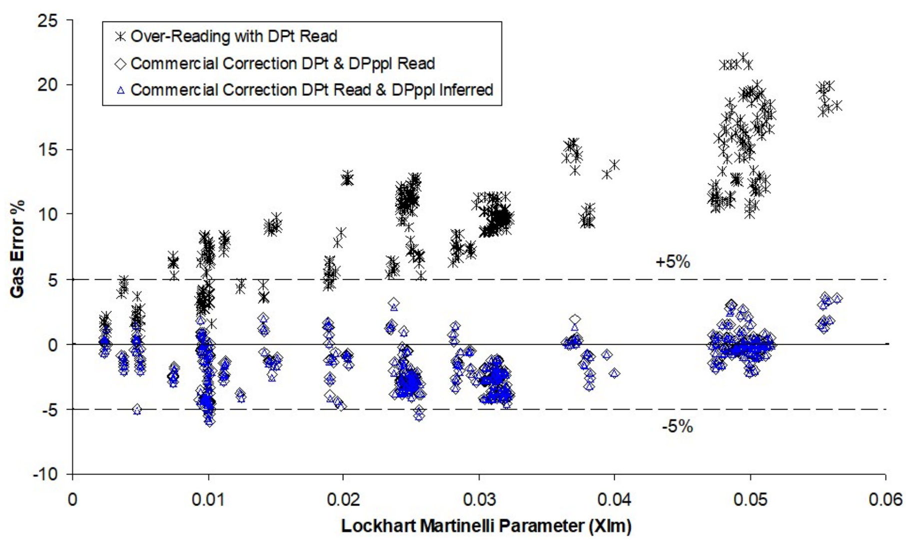


Fig 34. Wet Gas Venturi Meter Correlation Massed Data With Inferred PPL DP_{PPL}.

Hence, wet gas flow is an adverse flow condition for DP transmitters. The standard methodology only uses DP transmitters to read the primary and permanent pressure loss DPs. If either DP transmitter is compromised the wet gas meter system ceases to be operational. A level of redundancy in DP readings is therefore beneficial. The three DP transmitter Prognosis assembly offers the ability for the system to lose any one DP reading and still be operational.

$$\Delta P_t = \Delta P_r + \Delta P_{PPL} \quad (18)$$
$$\Delta P_{PPL} = \Delta P_t - \Delta P_r \quad (19)$$

The Prognosis three DP transmitter assembly allows the primary DP (ΔP_t) or PPL DP (ΔP_{PPL}) to be known even if any one of the three direct readings is lost. Figure 32 shows the result using the massed data if the primary DP transmitter is off-line and the primary DP is inferred from equation 18. Figure 33 shows the result using the massed data if the PPL DP transmitter is off-line and the PPL DP is inferred from equation 19. Such is the quality of modern DP transmitters that the missing third DP can be inferred from the useable two DP transmitters with low uncertainty and the system effectively continues to operate with minimal change to the gas flowrate prediction uncertainty.

Furthermore, it is possible to predict the Lockhart-Martinelli parameter of a wet gas flow through a Venturi meter via any one of three DP ratios available from using the Prognosis DP transmitter assembly, i.e.:
$X_{LM} = f(\Delta P_{PPL}/\Delta P_t) = f(\Delta P_r/\Delta P_t) = f(\Delta P_r/\Delta P_{PPL})$.

5 Field Example of Wet Gas Venturi Meter Running Prognosis

A 14", 0.4β Venturi meter running Prognosis is in service on an unmanned offshore platform. Permission to show this data is granted on the condition the owner and location information of this meter are withheld. This meter was calibrated to find the discharge coefficient and to be Prognosis ready. Figure 35 shows the Prognosis baseline gas flow calibration result (left side) and the result in service (right side).

In service the Prognosis result shows the gas Venturi meter has a problem. Pattern recognition identifies the issue *specifically* as wet gas flow. Figure 35 (right side) shows the PLR (represented by co-ordinate y_1) increasing as the problem increases. Whereas operators of standard wet gas Venturi meter systems *assume* a shift in PLR is due to wet gas liquid loading, the Prognosis based wet gas Venturi meter systems use Prognosis pattern recognition to *verify* that the issue is wet gas flow. Hence, here the operator now knows rather than assumes there is wet gas flow. The aim now is to find the apparent and actual gas mass flows, as well as the approximate liquid flowrates.

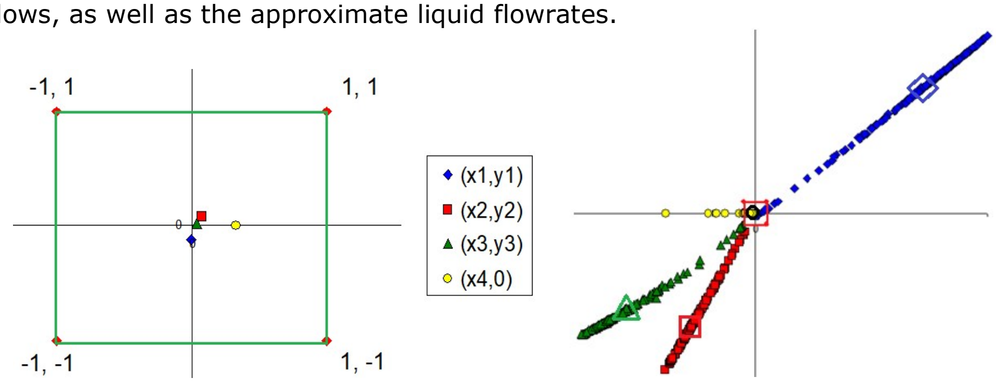


Fig 35. Lab Gas Flow (Left) and In-service (Right) Wet Gas Prognosis Results.

A challenge with all wet natural gas flows is to know the type of liquid, i.e. the water liquid mass ratio. In many cases from other operational evidence, e.g. sampling and downstream processing, the operator may have a good idea what the liquid is. In this case liquid hydrocarbon was first assumed, i.e. liquid density is approximated at 750 kg/m^3. This allows the ISO / TDFS wet gas Venturi meter correlation to estimate the Lockhart Martinelli parameter via. the $X_{LM} = f(PLR, DR, Fr_g)$ relationship. Figure 36 shows this meter's PLR over time. The instability typical of wet gas flow is evident. In this application the Lockhart Martinelli parameter was very small and the conditions suited the ISO TR 11583 correlation. Figure 37 shows the correlation's associated Lockhart-Martinelli

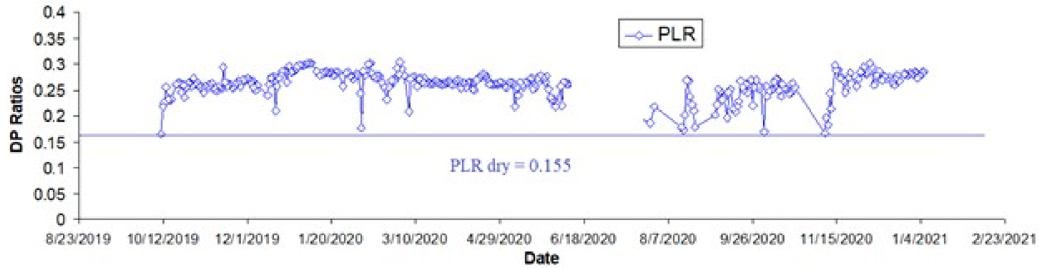


Fig 36. 14”, 0.4 Beta Venturi Meter PLR vs. Date.

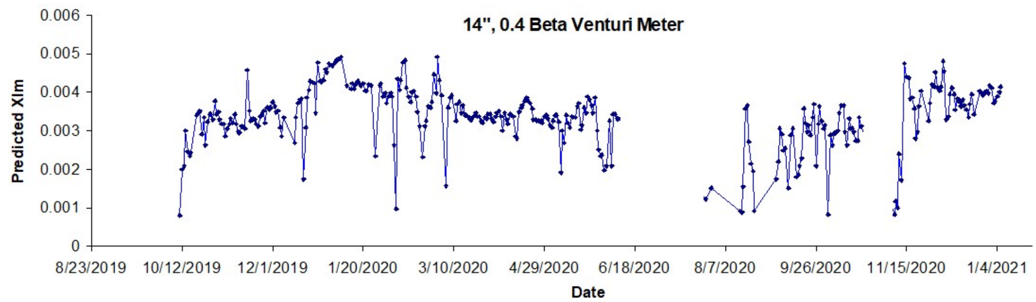


Fig 37. ISO TR 11583 / TDFS X_{LM} = f(PLR) Lockhart Martinelii Parameter Estimates.

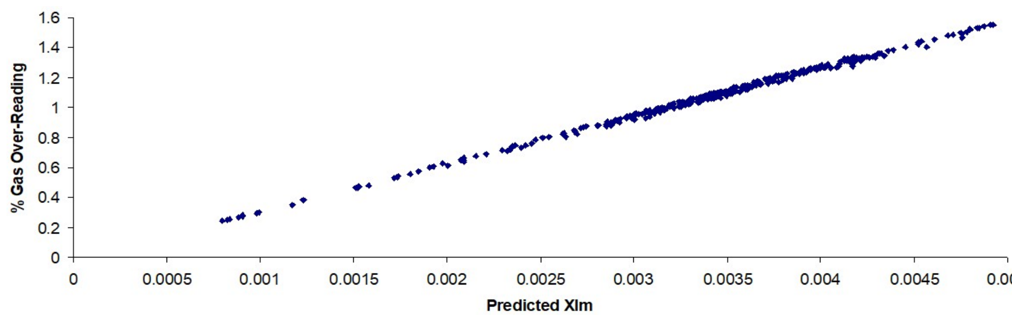


Fig 38. ISO TR 11583 / TDFS OR% = f(X_{LM}) Estimates.

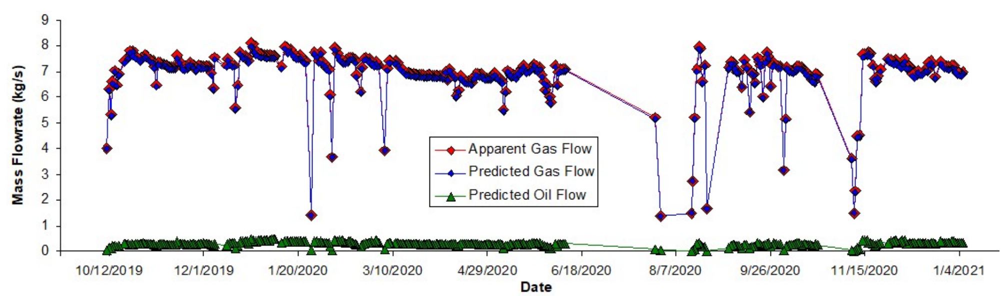


Fig 39. ISO TR 11583 / TDFS Calculated Apparent Gas Mass Flowrate, Actual Gas Mass Flowrate, and Liquid Mass Flowrate.

parameter predictions vs. time results. Fig 38 shows the correlation’s associated gas over-reading vs. Lockhart-Martinelli parameter results. Figure 39 shows the apparent (i.e. uncorrected) gas flow prediction, the actual (i.e. corrected) gas mass flowrate prediction, and the liquid mass flowrate prediction. The gas flowrate over-reading is an average of +1.1% from the calculated actual gas mass flowrate. The presence of approximately 25.1 tonnes/day of liquid is now reported.

If the liquid was not liquid hydrocarbon but water, then the results are not greatly changed. Using a water density of 999 kg/m^3 the gas flowrate over-reading is shown to be an average of +1.0% from the calculated actual gas mass flowrate. The presence of approximately 24.4 tonnes/day of liquid is now reported. Hence, the primary issue with whether the liquid is liquid hydrocarbon or water is whether the previously unnoticed liquid is valuable hydrocarbon or costly water. That information is usually found by sampling, downstream process data, or by the addition of water cut devices, but further discussion on this topic is outside this paper's scope.

6 USE OF EQUATIONS OF STATE ON KNOWN FLUID COMPOSITIONS

The liquid loading range of $X_{LM} \leq 0.06$ is an obvious limitation to the use of a stand-alone Venturi meter with a third pressure tap. Many upstream unprocessed natural gas production flows have considerably higher liquid loadings than $X_{LM} \leq 0.06$. Hence, for a stated fluid composition, industry often uses an appropriate Equation of State (EoS) to predict the gas to liquid mass ratio.

The total fluid composition often comes from the reservoir engineer estimates, or wet gas samples. With the total fluid composition known (or approximated) and the local pressure and temperature at the meter read, an appropriate EoS can estimate the gas to liquid mass flow ratio and phase densities at the meter. This offers another way to predict the Lockhart Martinelli parameter.

Various wet gas meter manufacturers have their own EoS based wet gas meter, but published checks on EoS effectiveness are rare. Hence, TDFS requested Accord ESL use their Peng Robinson EoS ('CHARM' - Compact Hydrocarbon Allocation Reference Model) on CEESI laboratory wet gas Venturi meter data of known composition to investigate the efficacy of using such an EoS as part of a wet gas Venturi meter system. The total mole composition of sample wet natural gas flows from an 6", 0.6β Venturi meter tests, and the accompanying pressure and temperature readings at the meter, where inputted to the CHARM EoS. No natural gas and hydrocarbon liquid reference flows were given. CHARM predicted the Gas Volume Fraction (GVF), and the gas and liquid densities, which was then converted to Lockhart Martinelli parameter predictions. Fig 40 shows the resulting CHARM predicted vs. laboratory reference Lockhart Martinelli parameter data.

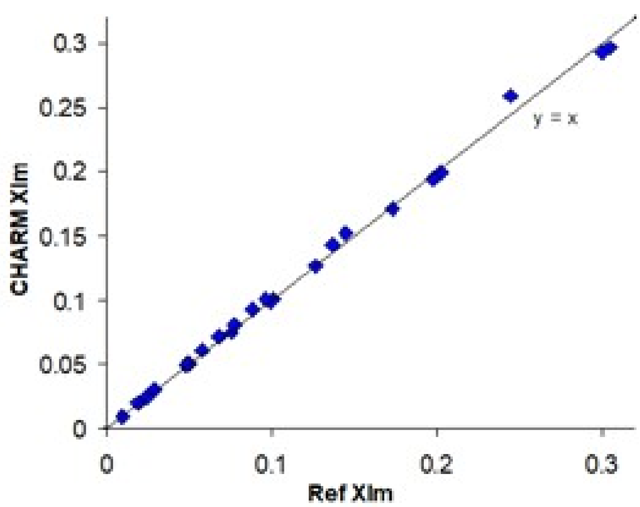


Fig 40. 6", 0.6β Wet Gas Venturi Meter CHARM X_{LM} Prediction Results.

Fig 40 shows the Lockhart Martinelli parameter prediction based on the CHARM Gas Volume Fraction (GVF) and gas and liquid density predictions. For a precisely known total fluid composition the CHARM Lockhart Martinelli parameter prediction is very close to the laboratory reference values. These Lockhart Martinelli parameter predictions can be substituted into the wet gas Venturi meter correlation, $OR=f(X_{LM},WLR_m,DR,Fr_g)$. Fig 41 shows the gas flow results of applying the TDFS wet gas Venturi meter correlation. The apparent gas mass flowrate was corrected to the actual gas mass flowrate to 3% uncertainty at 95% confidence. Fig 42 shows the corresponding liquid mass flowrate prediction performance.

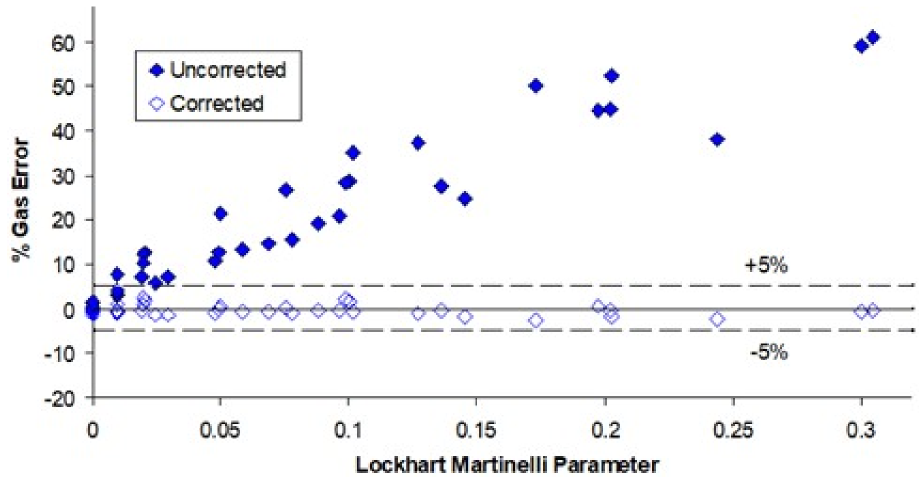


Fig 41. 6", 0.6β Wet Gas Venturi Meter Uncorrected and CHARM Based Liquid Loading Derived Corrected Gas Mass Flowrate.

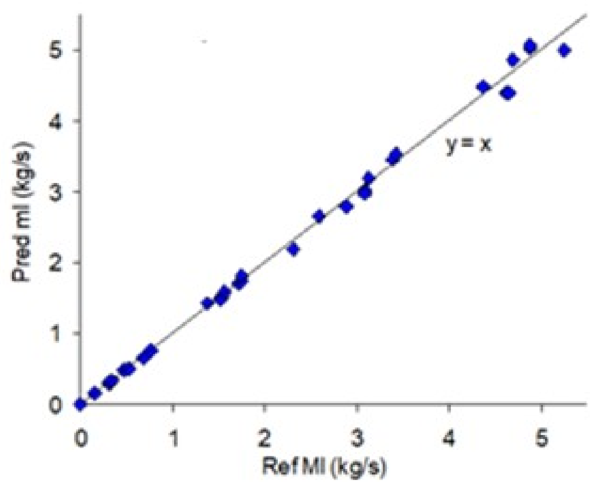


Fig 42. 6", 0.6β Wet Gas Venturi Meter CHARM Liquid Flow Results.

Naturally, the accuracy of an EoS's liquid loading prediction depends in part on the details of the fluid composition entered. The more detailed and more precise the fluid composition entered the more precise the result. In this example, detailed correct knowledge of the fluid composition was used. However, in the field it is probable that the total fluid composition will not be so precisely known. Hence, it is worthwhile considering the effect of imprecise fluid property inputs. Such practical realities are rarely discussed in manufacturer literature. Two examples are now given.

First consider the example where the ethane (C_2H_6) and propane (C_3H_8) component contribution are swapped around in the composition entry, i.e. the wet gas flows total composition with approximately 9% ethane and 1% propane is entered as 1% ethane and 9% propane. Figures 43 through 45 show that such fluid composition errors (labelled 'Imprecise Composition 1') have little effect on Lockhart Martinelli parameter, liquid flowrate, and or gas flowrate predictions. Perhaps this is to be expected, as these relatively light components don't appear much in the liquids. It is errors in the entry of the > C10+ components that could cause a more significant bias in predicted liquid loading. It is "… the heavies that tend to 'drop out'".

The second example shows the case where the data's relatively small quantity of C10+ components, which ranged from 0.3% to 18%, depending on the gas to liquid density ratio and Lockhart Martinelli parameter, were understated by 50%.

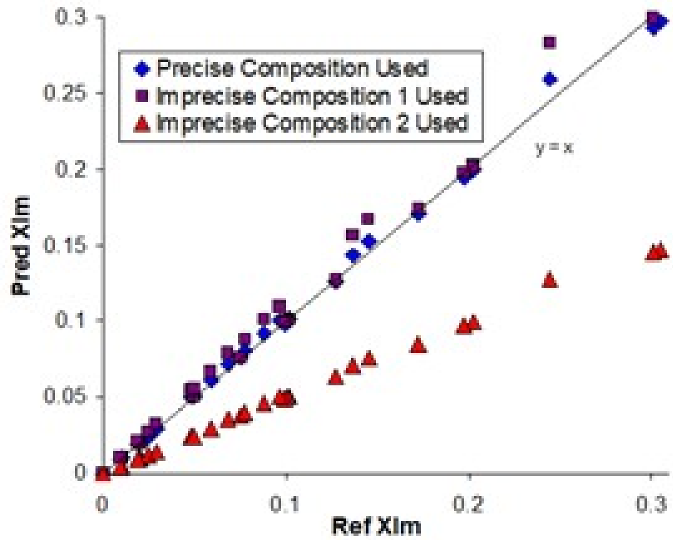


Fig 43. 6”, 0.6β Wet Gas Venturi Meter
With Different Fluid Composition CHARM X_{LM} Results.

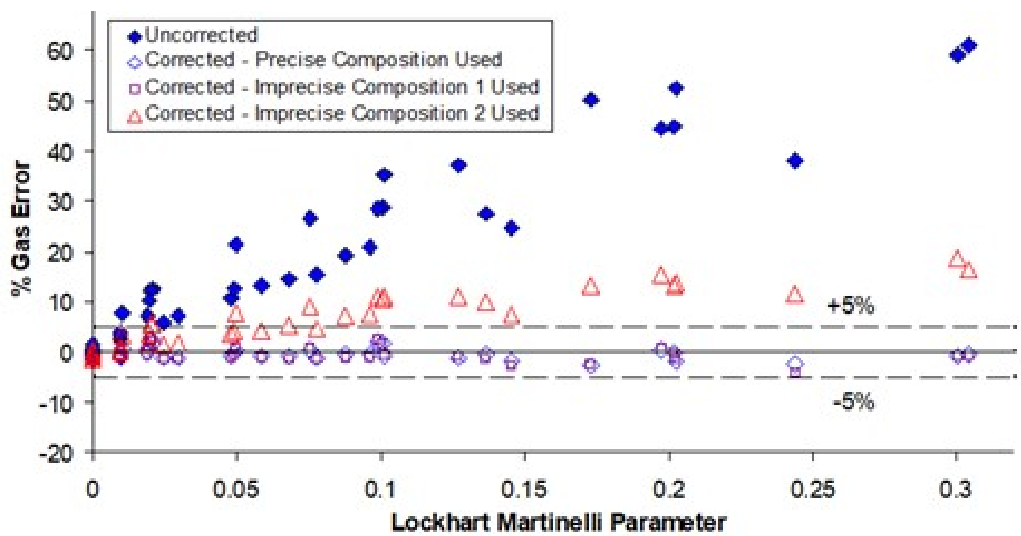


Fig 44. Uncorrected and CHARM Based Liquid Loading Derived Corrected Gas Mass Flowrate.

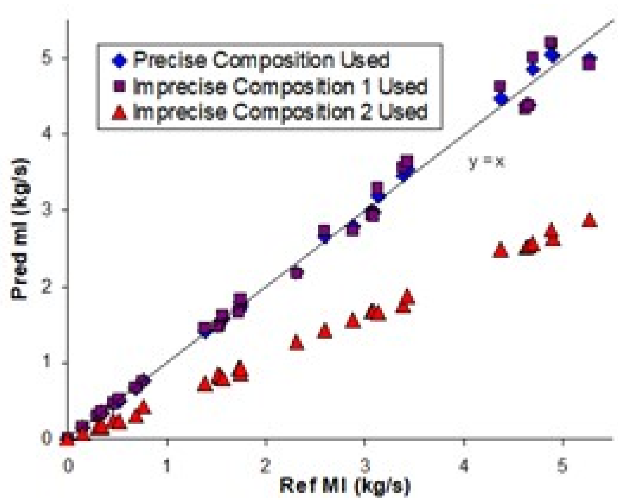


Fig 45. 6”, 0.6β Wet Gas Venturi Meter
With Different Fluid Composition CHARM Based Liquid Flow Results.

Figures 43 through 45 show that such fluid composition errors (labelled 'Imprecise Composition 2') has a more significant effect on Lockhart Martinelli parameter, liquid flowrate, and gas flowrate predictions. To predict the Lockhart Martinelli parameter reasonably well via an EoS it is necessary to know the precise fluid composition, i.e. 'garbage in garbage out'. The most significant challenge is to get a reasonably accurate estimate of the relatively small proportion of C10+ components in a wet natural gas flow.

For the case of $X_{LM} \leq 0.06$ where the fluid composition is known, there is the ability to predict the Lockhart Martinelli parameter with both the $X_{LM}=f(PLR)$ correlation, and the EoS. Hence, there is potential to further refine the results by introducing data validation and reconciliation techniques, e.g. Stockton [10,11].

7 THE EFFECT OF BURRS ON WET GAS VENTURI METERS

Fig 46. Venturi Pressure Port Burr.

ISO 5167 states all protrusions on a gas Venturi meter's pressure ports should be removed. Any burrs remaining from manufacturing will cause DP and flowrate prediction biases. However, due to some considering Venturi meters just a commodity, to reduce cost, some are farming out manufacturing to non-flow meter specialist fabrication shops. Then, if the drawing doesn't say clean all burrs it usually is not done.

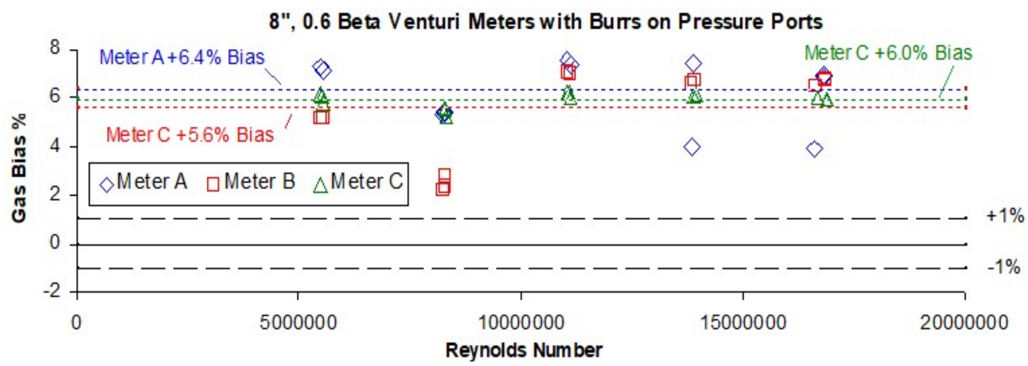


Fig. 46. Gas Flow Performance of 8", 0.6β Venturi Meters Burrs on Pressure Ports.

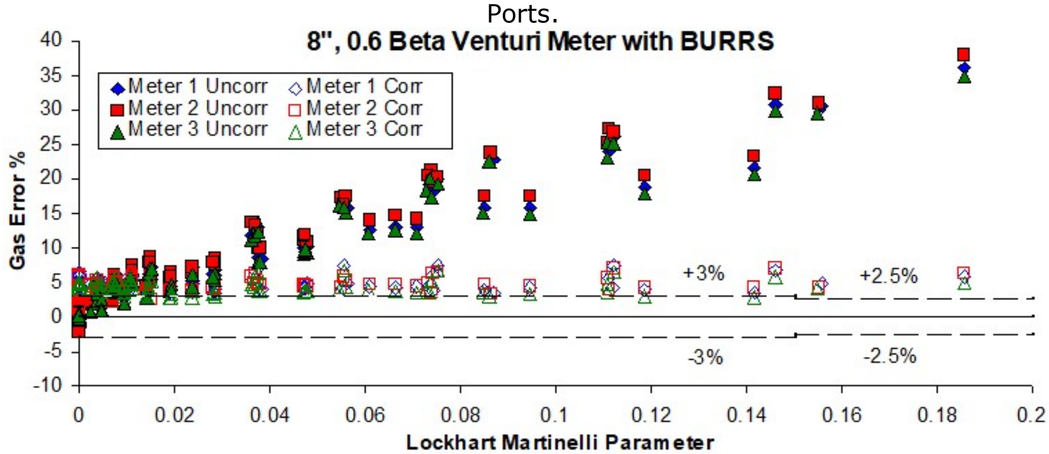


Fig 47. Wet Gas Flow Performance of 8", 0.6β Venturi Meters with Burrs on Pressure Ports.

Hence, some Venturi meters made by non-specialist fabrication shops are going to calibration with pressure port burrs (see Fig 46). Fig 47 shows the single phase gas flow performance of three Venturi meters with burrs. There is a bias induced of approximately +6%.

Fig 47 shows the wet gas performance of these three Venturi meters. Whereas it could be assumed the effect of burrs become incidental with wet gas flow this is not the case. The bias remains evident after the wet gas correction is applied. These meters subsequently had the burrs removed and then performed correctly in single phase and wet gas flows. Good practice for single phase gas meters is generally good practice for wet gas meters.

8 CONCLUSIONS

Using 3rd party independent massed data the ISO TR 11583 horizontally installed Venturi meter wet gas correlations have been shown again to work well. For a known Lockhart Martinelli parameter the ISO $OR=f(X_{LM})$ was shown to be accurate, predicting the gas flowrate to the ≈3 % uncertainty. The independent massed data indicated Reader Harris's suggestion of assuming a linear relationship between the liquid hydrocarbon and water correlations gave reasonable results for multiphase wet gas flows. Furthermore, some of this ISO correlation's limits can be broadened, specifically it works down to $Fr_{g,th}>2$. However, extrapolating this ISO correlation to $DR<0.02$ produced higher uncertainty. Nevertheless, it has been shown again that commercial correlations based on wider ranging data than ISO can potentially produce incremental improvements. As an example, TDFS used this massed independent wet gas data to produce a $OR\%=f(X_{LM})$ wet gas Venturi meter correlation to 2.5% uncertainty across a marginally wider wet gas flow range than ISO TR 11583.

The coupling of ISO TR 11583 horizontally installed Venturi meter $X_{LM}=f(PLR)$ & $OR=f(X_{LM})$ correlations gave a gas mass flowrate prediction 5% uncertainty, as stated by ISO, *but only within the very limited range of the correlation*. However, often with the massed data the results were $Y/Y_{max} > 0.7$ and the ISO correlation was *not* applicable. Furthermore, there is no minimum X_{LM} limit where an ISO $X_{LM}=f(PLR)$ correlation is guaranteed. This then, is a primary reason why industry does not adopt the ISO TR 11583 wet gas Venturi meter as a staple economic wet gas metering methodology. However, TDFS has analysed 34 Venturi meter wet gas data sets and found that the published ISO $X_{LM}=f(PLR)$ correlation is rather conservative. It is possible to fit an alternative $X_{LM}=f(PLR)$ correlation that will give a guaranteed X_{LM} prediction within the range $0<X_{LM}\leq 0.06$.

One commercial $X_{LM}=f(PLR)$ & $OR=f(X_{LM})$ correlation produced an algorithm which gave a Lockhart Martinelli parameter prediction for every one of the massed data's 701 eligible wet gas points within the $X_{LM} \leq 0.06$ range, and a gas mass flowrate prediction uncertainty of 4.2% at 95% confidence. Whereas $X_{LM} \leq 0.06$ is only 20% of the ISO defined wet gas range of $X_{LM} \leq 0.3$, it is a range of wet gas liquid loading where many wet gas meters are required.

For wet gas liquid loadings at $0<X_{LM}\leq 0.3$, if the reservoir engineering fluid composition is available and accurate, it has been shown that it is a valid approach to predict the Lockhart Martinelli parameter via a suitable Equation of State. Using Accord ESL's industry tried and tested Equation of State ('CHARM') use of a precise fluid composition gave very good Lockhart Martinelli parameter predictions. However, a subtlety not often discussed by industry is that an Equation of State's Lockhart Martinelli parameter prediction accuracy is highly dependent on the operator having a reasonably accurate understanding of the flows total fluid composition. In particular, to avoid significant Lockhart Martinelli

parameter and gas mass flowrate prediction biases it is important that the relatively small quantity of the heavier components >C10+ be correctly stated.

Finally, it was shown that the Venturi meter diagnostic system can specifically identify wet gas flow from other meter malfunctions that also cause a PLR shift. Hence, use of Prognosis assures the operator that the wet gas X_{LM} = f(PLR) correlation is being correctly applied to wet gas flow and not erroneously when the PLR shifts for other reasons. Furthermore, the Prognosis three DP transmitter assembly offers more DP transmitter redundancy than the standard set up.

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