Comparisons of Ultrasonic and Differential Pressure Meter Responses to Wet Natural Gas Flow

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1. Introduction

Wet natural gas flow metering is important to natural gas producers. Whereas there are multiphase wet gas meter designs available, due to economic constraints the majority of wet natural gas flows are still metered by single phase gas flow meter technologies. However, there is limited independent, neutral, third party published information regarding the direct comparison of different gas meter design performance in wet gas flow service.

Gas meter manufacturers have to varying extents researched their respective meter's wet gas performance, sometimes made limited modifications, and their sales teams promote the pros and play down the cons to their best advantage. Due to limited knowledge in this specialised and complex subject, and the lack of published literature directly comparing different meter types, many operators can find themselves largely reliant on the advice of these salesmen. However, these salesmen naturally have a professional duty and vested financial interest to promote their technology over competing technologies regardless of the true performance comparisons. Furthermore, human nature can also cause the "Marlow's hammer[1]" effect, where salesmen come to genuinely believe their product is best for that particular application regardless of what independent data may show. Operators would therefore benefit from more 3rd party comparisons of different gas meter technologies in wet gas service.

Two popular gas flow meter designs are the ultrasonic meter (USM) and the Differential Pressure (DP) meter. The DP meter is one of the most widely used flow meter designs for both gas and wet gas flow applications. The USM share of the gas market is growing, and some USM manufacturers are now marketing the USM as a replacement for DP meters in wet gas flow applications. However, there is limited public literature that directly compares DP & USM meter wet gas flow performance. In this paper the wet gas flow performance of ultrasonic, orifice DP & Venturi DP meters are discussed, using 3rd party published information, and data taken from 8" meters being tested in series at the CEESI Wet Gas Test Facility. The performance review includes the respective meters liquid induced gas flow rate prediction biases and the respective liquid loading monitoring systems.

2. Wet Gas Flow Terminology

A wet gas flow is defined by ISO [1, 2] & ASME [3] as any two-phase (liquid and gas) flow where the Lockhart-Martinelli parameter (X_{LM}) is less or equal to 0.3, i.e. $X_{LM} \leq 0.3$. Note that this definition covers any combination of gaseous and liquid components.

The Lockhart-Martinelli parameter (equation 1) indicates the relative amount of total liquid with the gas flow. Note that m_g & 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 average gas and liquid densities respectively.

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

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[1] Marlow's Hammer: "If the only tool you have is a hammer every job looks like a nail".

The term ‘liquid loading’ is widely used as a qualitative term to describe the amount of liquid with a gas flow.

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), shown as equations 2, is a non-dimensional expression of the gas & liquid flow rates, where g is the gravitational constant, D is the meter inlet diameter and A is the meter inlet cross sectional area.

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

Single liquid component wet gas flows have one liquid density. Multiphase wet gas flows have two liquid densities (water and liquid hydrocarbon, ‘LHC’). In this case the liquid density used to calculate the gas to liquid density ratio and the gas densiometric Froude number is the average liquid density.

“Water cut” is the ratio of the water to total liquid (i.e. the sum of water and LHC) volume flow rates when the fluid is at ***standard*** conditions. In this paper “water to liquid mass ratio” (or “WLR_m”) is defined as the ratio of the water to total liquid ***mass*** flow rates. The use of mass flow removes the requirement to define the flow conditions. The WLR_m is shown as equation 3, where m_w is the water mass flow rate and m_{lhc} is the LHC mass flow rate.

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

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

$$\rho_{l,\hom} = \frac{\rho_w \rho_{lh}}{(\rho_{lh}\, WLR_m) + \rho_w(1 - WLR_m)} \quad \text{--- (4)}$$

Equation 5 shows the generic DP meter gas mass flow equation, where E is the velocity of approach (i.e. 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 differential pressure (DP). Wet gas flow conditions tend to cause a DP meter to have a positive bias in the gas flow rate prediction. This is often called an “over-reading” and denoted as “OR”. The DP created by a wet gas (ΔP_{tp}) is different to when that gas flows alone (ΔP_g). The result is an erroneous, or “apparent”, gas mass flow rate prediction, $m_{g\ apparent}$ (see Equation 6). The over-reading is expressed either as a ratio (equation 7) or percentage (equation 7a) comparison of the apparent to actual gas mass flow rate.

$$m_g = EA_t C_d \varepsilon \sqrt{2\rho_g \Delta P_g} \quad \text{--- (5)} \qquad m_{g\,apparent} \approx EA_t C_d \varepsilon \sqrt{2\rho_g \Delta P_{tp}} \quad \text{--- (6)}$$

$$OR = \frac{m_{g\,Apparent}}{m_g} = \frac{\varepsilon_{tp} C_{d,tp}}{\varepsilon C_d}\sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} \cong \sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} \quad \text{--- (7)}$$

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

3. Flow Patterns

The liquid dispersion in a wet gas flow (i.e. the ‘flow pattern’) depends on flow conditions. Flow patterns significantly affect any gas meters wet gas response. The flow pattern is dictated by liquid properties and the gas dynamic pressure. Low gas dynamic pressure (i.e. low gas density and / or low gas velocity) means the liquids weight dominates and the liquid runs on the base of a horizontal pipe (see Figure 1). High gas dynamic pressure (i.e. high gas density and / or high gas velocity) means the gas dynamic pressure dominates and the liquid flows as an annular mist flow (see Figure 3). Moderate gas dynamic pressure produces a transitional flow pattern between stratified and annular mist flow (see Figure 2). Many horizontal wet natural gas production flows are in the stratified / annular mist transition zone.

Fig 1. Gas/HCL stratified.

Fig 2. Gas/HCL transition.

Fig 3.Gas/HCL annular.

The flow pattern influences a gas ultrasonic meter as it affects the local gas velocity and the fluid phases across each individual path. The flow pattern influences a DP meter as it influences the DP created through the DP meter body.

4. DP & Ultrasonic Meter Wet Gas Response

It is in the interest of both operators and gas meter manufacturers that relatively low cost simple gas meters can cope with wet gas flow applications. Therefore, there tends to be a “can do!” attitude to the problem. However, over time this attitude can begin to give a false perception that wet gas flow metering is an adverse flow condition that various gas meter technologies can comfortably deal with. In reality wet gas flow is an **extremely** adverse flow condition that **all** gas meters struggle with.

Wet gas flow causes all gas meter technologies severe problems. What constitutes a ‘good’ gas meter response to wet gas flow is wholly subjective. Compared to dry gas flow meter specifications all gas meter wet gas capabilities are poor. This reality is seldom discussed in the industry. There tends to be more focus on any positive aspect of a gas meters performance with wet gas flow while the negative aspects tend to be down played. DP and ultrasonic meters responses to wet gas flows should be considered in context. The question is not really which single phase gas meter has the ***best*** response to wet gas flow, but rather, which gas meter design manages to deliver the most useful amount of information when used in wet gas flow applications.

4a. Differential Pressure (DP) Meter Wet Gas Response

The response of DP meters to wet gas flow has been actively researched for nearly sixty years. The response of the orifice meter and Venturi meter to wet gas flow is now so well understood that ISO has published wet gas correction factors for these meters. The existence

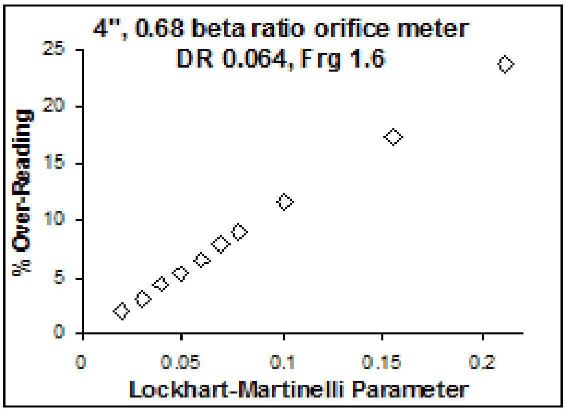

Fig 4. The Liquid Loading Effect.

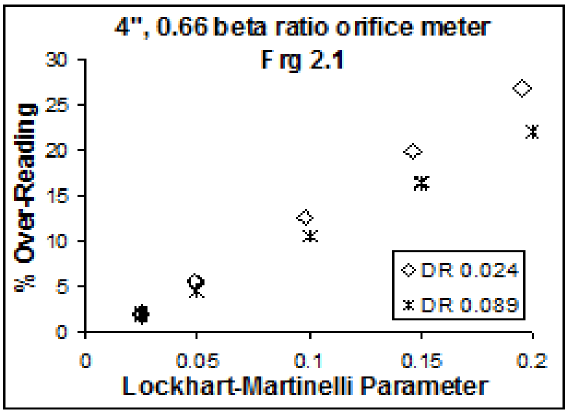

Fig 5. Gas to Liquid Density Ratio Effect.

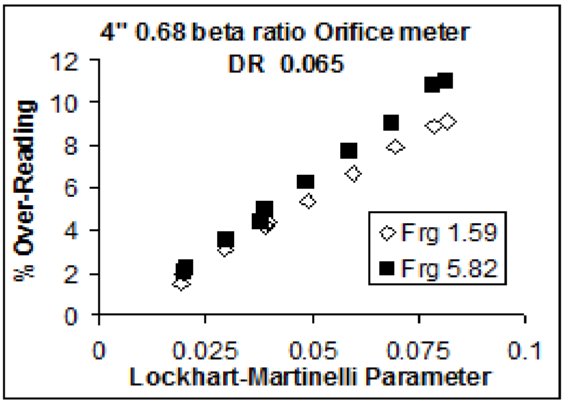

Fig 6. Gas Densiometric Froude Number Effect.

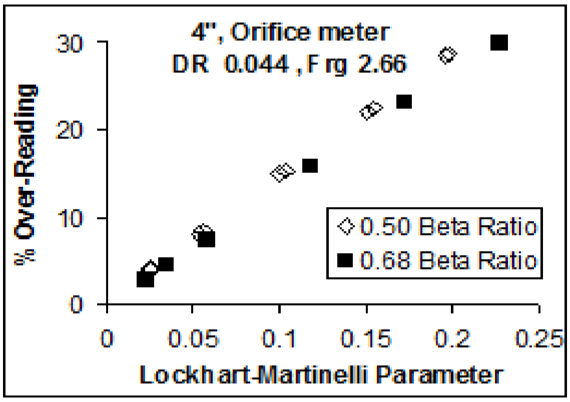

Fig 7. The Beta Effect.

of an ISO correlation states that the wet gas response of that meter is so well understood, and is known to be so reproducible, that there can be confidence it can be accurately predicted. (The lack of a wet gas flow meter correlation for any meter infers the opposite is true.) It is now known that:

- an increasing liquid loading / Lockhart Martinelli parameter produces an increasing over-reading (see Figure 4, & Schuster & Murdock [4, 5]). Figure 4 (i.e. a X_{LM} vs. %OR plot) is now commonly called a 'Murdock plot'
- the scale of the wet gas over-reading of various generic DP meter designs is related to the gas to liquid density ratio (see Figure 5, & Chisholm [6, 7 & 8]).
- the scale of the wet gas over-reading of various generic DP meter designs is related to the gas densiometric Froude number (see Figure 6, De Leeuw [9] & Hall et al [10]).
- the scale of the wet gas over-reading of various generic DP meter designs is related to the DP meter beta value (see Figure 7, Stewart et al [11, 12] & Hall et al [10])
- the scale of the wet gas over-reading of various generic DP meter designs is related to the liquid properties (see Figure 8, Steven et al [13] & Reader-Harris et al [14, 15])
- the scale of the wet gas over-reading of various generic DP meter designs is related to the meter / flow orientation (see Britton et al [17] & Graham et al [18])

Between 1997 & 2011 de Leeuw [9], and Hall & Steven et al [10, 16] linked the DP meters over-reading to the flow pattern. For a given DP meter design, pipe size, beta value & flow orientation, varying the Lockhart Martinelli parameter, gas to liquid density, gas densiometric Froude number and /or water to liquid mass ratio means changing the flow pattern, and hence the DP meter's over-reading.

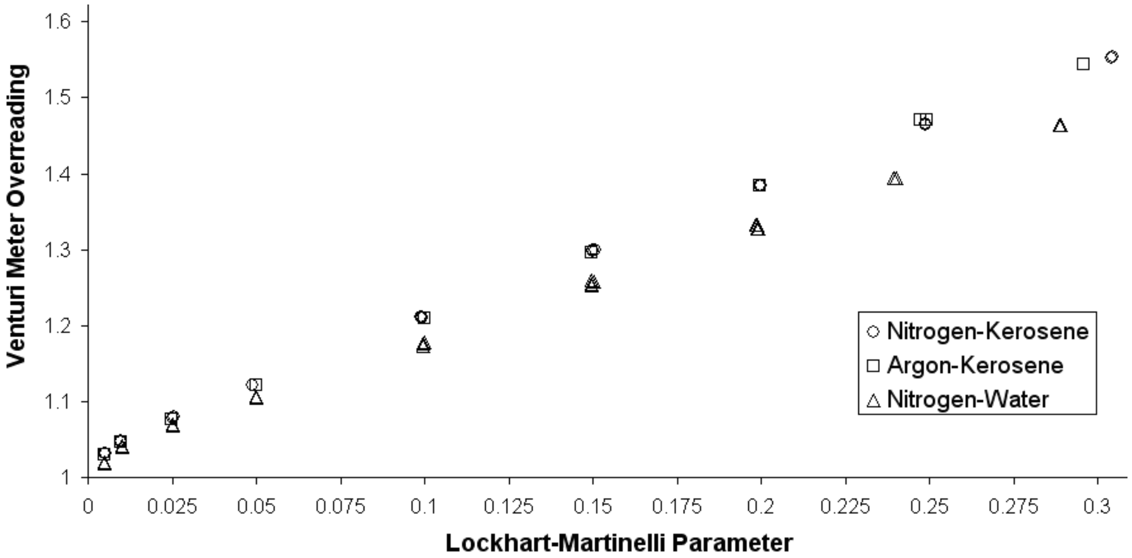

Fig 8. Influence of Liquid Properties on Venturi Meter Wet Gas Flow Over-Reading.

The response of orifice and Venturi DP meters to wet gas flow is now so well researched and understood that ISO has technical reports with orifice and Venturi meter correlations. The DP meter's wet gas flow response has been found via massed long term multi-company R&D to be not just repeatable, but highly reproducible.

Orifice Meters

ISO TR 11583 [1] and ISO TR 12748 [2] both give the same orifice meter wet gas correlation, for 2" to 4" meters, horizontally installed, with gas and liquid hydrocarbon. ISO TR 12748 [2] includes a modification to this orifice meter correlation that accounts for the effect of the water to liquid mass ratio. These orifice meter wet gas correlation were developed and checked over several years by cross industry cooperation (including multiple operators, meter manufacturers, Joint Industry Projects and test facilities). Figures 9 thru 11 show photographs of various 2" to 4" orifice meter wet gas flow tests carried out by industry in the last decade. These orifice meter correlations are valid for all paddle plate, single & dual chamber orifice meter designs that are ISO 5167 compliant. These ISO wet gas orifice meter correlations are not orifice meter (or DP transmitter) manufacturer type dependent. They were produced by industry wide collaboration, i.e. by industry for industry, and are freely available to all. Orifice meter technology has now reached the stage where any 2" to 4" orifice meter, supplied "off the shelf" by any reputable supplier, has a known wet gas flow performance that is accurately predicted by a freely available ISO published wet gas correlation.

Figure 13 reproduces a massed orifice meter wet gas data set (see Steven et al [16]) with and without the ISO correction factor applied. For a known liquid flow rate the ISO correlation corrected the data to within 2% uncertainty (to 95% confidence). All data used (from multiple operators, test facilities and orifice meter manufacturers) was traceable.

Table 1 shows the wide wet gas flow condition ranges for which the ISO orifice meter wet gas correlation is applicable. The massed data sets from Murdock, Chisholm and others were not used as they were not traceable. However, that data was ***also*** noted to agree with the traceable data and the ISO correlations.

Fig 9. 4" Dual Chamber Orifice Meter Multiphase Wet Gas Flow Tests at CEESI.

Fig 10. 2" Paddle Plate Orifice Meter Multiphase Wet Gas Flow Tests at CEESI.

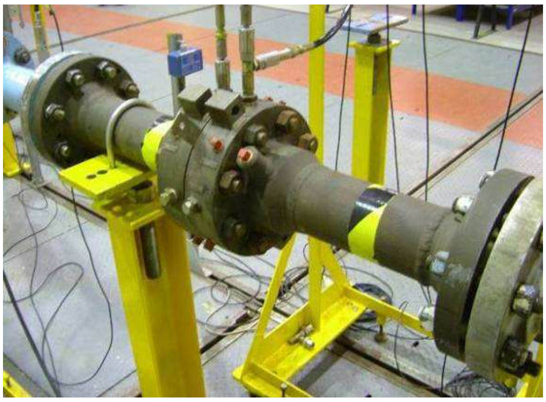

Fig 11. 4" Paddle Plate Orifice Meter Two-Phase Wet Gas Flow Tests at TUVNEL.

Fig 12. 8" Dual Chamber Orifice Meter Multiphase Wet Gas Flow Tests at CEESI.

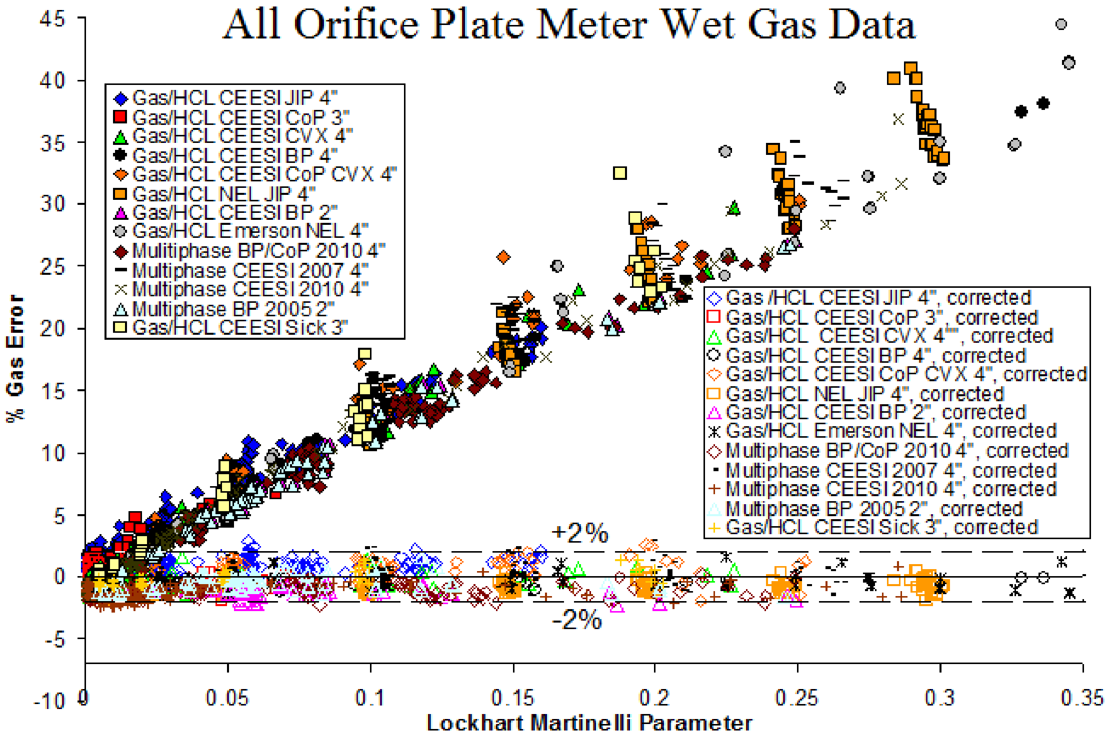

Fig 13. Massed 2" to 4" Orifice Meter Wet Gas Data With & Without the ISO Correlaton.

Parameter	Range
Pressure	6.7 to 78.9 bara
Gas to liquid density ratio	$0.0066 < DR < 0.111$
Fr_g range	$0.22 < Frg < 7.25$
X_{LM}	$0 \leq X_{LM} < 0.55$
Inside full bore diameter	$1.94” \leq D \leq 4.026”$
Beta	$0.341 \leq \beta \leq 0.683$
Gas / Liquid phase	Gas / LHC/ Water

Table 1. ISO TR12748 Multiphase Wet Gas Flow Orifice Meter Correlation Flow Range.

Industry has more understanding of orifice meter wet gas flow response than that stated in these ISO documents. In 1993 Ting [19] showed that at trace liquid loadings an orifice meter may very slightly under-read the gas flow rate. However, this under-reading is so slight it is within the uncertainty of most gas meter wet gas correction factors (i.e. 2%) and is therefore usually ignored.

In 2014 BP (Steven et al [20]) showed 4” wet gas orifice meter data (recorded at CEESI) where the liquid components included water, hydrocarbon liquid with heavier components (that would form wax below approximately 97^0F) and MEG injection. Although the ISO orifice meter wet gas correlation was extrapolated to different fluid properties it was shown to operate within the stated uncertainty.

In 2014 CEESI (Steven et al [20]) showed massed CEESI 8”, 0.689β orifice meter wet gas flow data. In 2015 new data has been added from this meter. Figure 12 shows this meter installation. Table 2 shows the data set range.

Parameter	Range
Pressure	$14 \leq$ Pressure (bar a) ≤ 77
Gas to liquid density ratio	$0.011 < DR < 0.083$
Fr_g range	$0.5 < Frg < 3.4$
X_{LM}	$0 \leq Xlm < 0.275$
Inside full bore diameter	0.2027 m (7.981 inch)
Beta	$0.689 \leq \beta \leq 0.752$
Gas / Liquid phase	Natural gas / Exxsol D80 / Water
WLRm	$0 \leq WLR_m \leq 1$

Table 2. 8” Orifice Meter Wet Gas Test Data Set

As the ISO TR 12748 orifice meter wet gas flow correlation is specifically for $2” \leq \Phi \leq 4”$ the correlation is being extrapolated when used with an 8” orifice meter. The results of applying the ISO correlation are shown in Figure 14. Extrapolating the 2011 orifice meter wet gas correlation for use with the 8” orifice meter wet gas flow data produces results slightly out with the correlations stated uncertainty of 2% at 95% confidence. The ‘corrected’ data show a slight positive bias. With no available alternative it is still beneficial to extrapolate the correlation, although the uncertainty has increased. When applying the ISO ≤ 4” orifice meter wet gas correlation to an 8” orifice meter the uncertainty was found to be -2% to +3% to 95% confidence.

Industry knows a lot about an orifice meters reaction to wet gas flow. The orifice meter does not cause damming problems and the DP signal is pseudo steady (see Steven et al [16]). The generic orifice meter wet gas flow response is not just repeatable, but reproducible, and therefore very predictable. For ≤ 8” nominal meter size ISO offers a reliable orifice meter wet

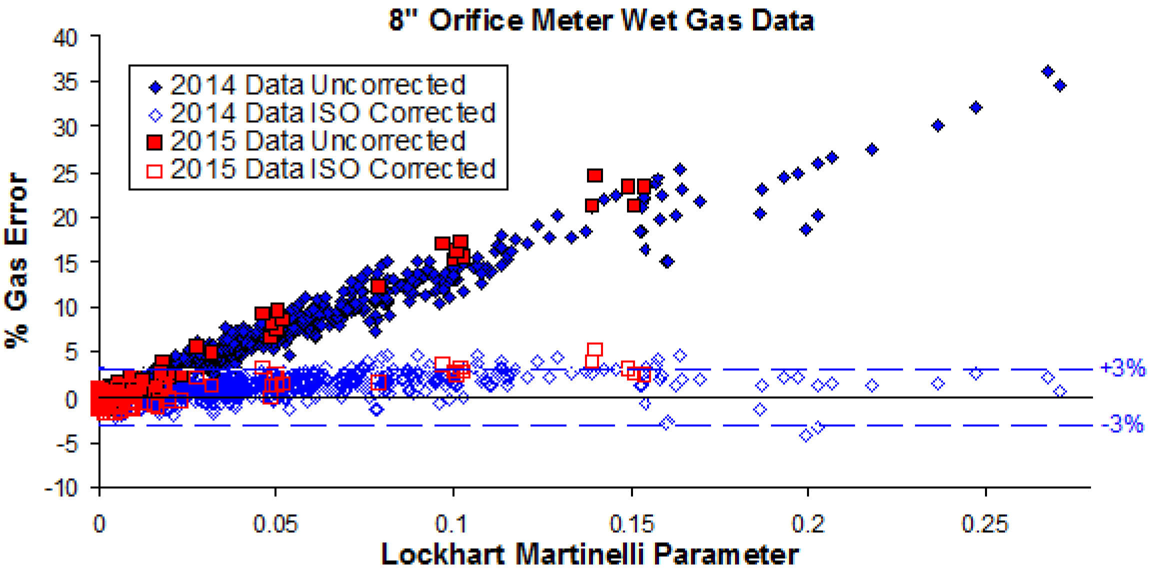

Fig 14. All CEESI 8” Orifice Meter Wet Gas Data.

gas correlation which for a known liquid flow rate corrects the gas flow rate prediction to 3% uncertainty. With the exception of the Venturi meter industry has no equivalent detailed knowledge of any other gas meter’s reaction to wet gas flow.

Venturi Meters

ISO TR 11583 [1] gives a Venturi meter wet gas correlation, for ≥ 2” horizontally installed meters with gas and LHC or gas and water. This ISO Venturi meter wet gas correlation was released after many years of Venturi meter wet gas flow research. Although largely uncoordinated, this research spanned more than two decades and was conducted by multiple operators, meter manufacturers, Joint Industry Projects, academics and test facilities. Figures 15 thru 18 show photographs of Venturi meter wet gas flow tests carried out at CEESI.

This ISO wet gas Venturi meter correlation is not Venturi meter (or DP transmitter) manufacturer type dependent and is valid for all ≥ 2” ISO 5167 compliant Venturi meters. It was produced by a UK government funded R&D project at TUVNEL. Originally considered controversial largely due to its release as an ISO correlation before it had been checked with independent data by 3rd parties, subsequent industry checks are now validating the general applicability of this correlation.

Figure 19 shows one such validation check, i.e. data from nominal 2”, 4”, 6” & 8” 0.6 beta ISO compliant Venturi meters tested at the CEESI multiphase wet gas data (i.e. the meters shown in Figures 15 through 18) with and without the ISO TR 11583 correction factor applied. The 8” & 4” meters are resident downstream of commercial equipment tests at the CEESI 8” & 4” multiphase wet gas test facilities respectively. The 2” & 6” meters were tested as downstream additions to various commercial jobs, and these data sets are therefore more limited. The ISO TR 11583 correlation is technically applicable only to gas with liquid hydrocarbon **or** gas with water. However, it is a simple procedure to interpolate between the two cases to apply the correlation to multiphase wet gas flows, i.e. gas with liquid hydrocarbon **and** water flows. For a known liquid flow rate, within the specified range of the ISO correlation, all four Venturi meter gas flow rate predictions predicted the gas flow to < 3% at 95% confidence. This is very close to the correlation uncertainty claim by ISO of 3% uncertainty for $X_{LM} \leq 0.15$, and 2.5% uncertainty for $0.15 < X_{LM} \leq 0.3$. This independent CEESI data showed that a 3% uncertainty for $X_{LM} \leq 0.15$ was achieved, but the uncertainty at

Fig 15. 8” Venturi Meter
Multiphase Wet Gas Flow Tests.

Fig 16. 6” Venturi Meter
Multiphase Wet Gas Flow Tests.

Fig 17. 4” Venturi Meter
Two-Phase Wet Gas Flow Tests.

Fig 18. 2” Venturi Meter
Multiphase Wet Gas Flow Tests.

the $0.15 < X_{LM} \leq 0.3$ range was still 3%, not 2.5%. At the $0.15 < X_{LM} \leq 0.3$ range the ISO correlation appears to very slightly over correct for the over-reading. However, an ISO Venturi meter correlation applicable over a wide range of Venturi meter sizes, that corrects a Venturi meter wet gas over-reading for a known liquid flow rate to 3% uncertainty is very useful to industry. Table 3 shows the range of the data sets shown in Figure 19.

Parameter	CEESI Test Range	ISO TR 11583 Stated Limits
Pressure	14.8 to 77 bara	N/A
Gas to liquid DR	$0.016 < DR < 0.085$	$DR > 0.02$
Fr_g range	$0.25 < Frg < 7.13$	$Fr_g > 3\beta^{2.5}$
X_{LM}	$0 \leq X_{LM} < 0.28$	$X_{LM} < 0.3$
Inlet Diameter	1.939” ≤ D ≤ 7.981”	D ≥ 2”
Beta	0.600	$0.4 \leq \beta \leq 0.75$
Gas / Liquid phase	Gas /HCL/ Water	Gas / HCL or Gas / Water

Table 3. CEESI 2” to 8” Venturi Meter Wet Gas Test Data Shown in Figure 19 & the ISO TR 11583 Venturi Meter Wet Gas Flow Correlation Flow Ranges.

The 2”, 0.6 beta Venturi meter data shown in Figure 19 (and included in Table 3) was only part of the total data set recorded from that meter. In Figure 19 / Table 3 the minimum density ratio (DR) included for all meters is 0.016. The ISO TR 11583 correlation is for DR > 0.02. It was considered reasonable to extrapolate the correlation to allow for this slightly

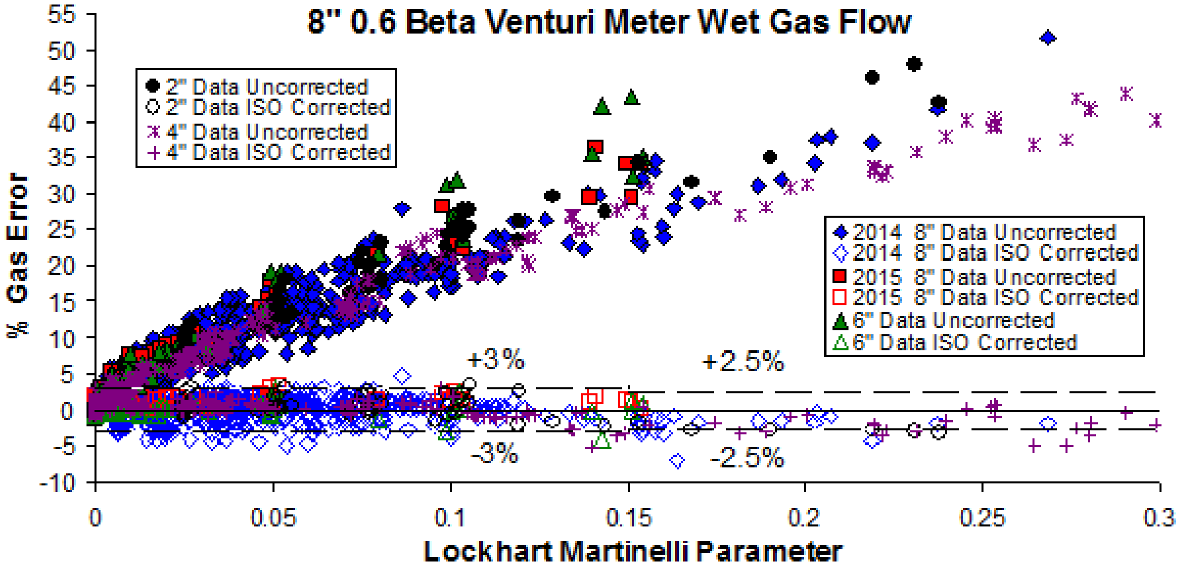

Fig 19. CEESI 2” to 8” Venturi Meter Multiphase Wet Gas Data
With & Without the ISO Correlaton.

lower value of DR. The same was true of the meter diameter limit. Although the correlation is for diameters > 50mm, the 2” sch 80 meter diameter is 1.938” / 49.2mm. It was considered reasonable to extrapolate the correlation to allow for the very slightly lower meter size. However, this meter’s wet gas data set also included data recorded at even lower density ratios, approximately 0.01. This is half the stated 0.02 minimum and hence it was considered unreasonable to include this data in the massed data set presented in Figure 19. With a slight diameter extrapolation and a liquid type interpolation already being applied a significant additional density ratio extrapolation would not be a fare review.

Figure 20 shows all the 2” meter data. The data is split between the ISO correlation valid range of DR > 0.02, and the ISO correlation invalid range of DR < 0.02. The ISO correlation predicted the gas flow rate of the DR > 0.02 data to 3% uncertainty. The extrapolated ISO correlation predicted the gas flow rate of the DR < 0.02 data to 5.1% uncertainty at 95% confidence. (The 34 test points at DR < 0.02 showed a correlation uncertainty of 5% at 94%

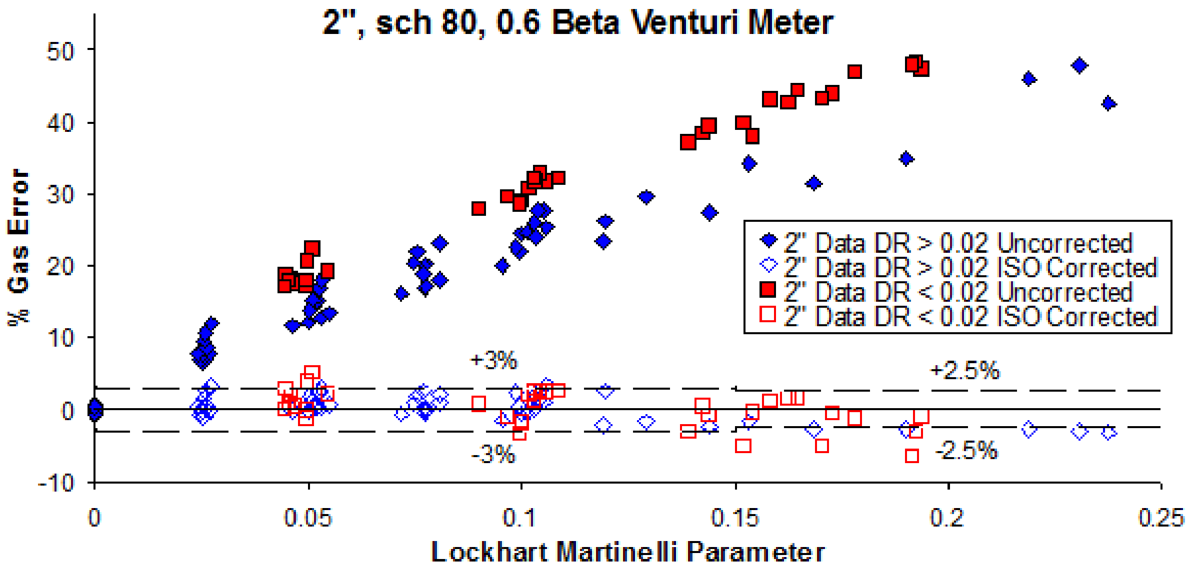

Fig 20. CEESI 2” Venturi Meter Multiphase Wet Gas Data, Full Data Set,
Inclusive of DR < 0.02.

confidence.) This result shows that modest density ratio extrapolation of the correlation does not cause gross errors in this correlation’s output.

Venturi meter technology has reached the stage where any ≥ 2” ISO compliant Venturi meter, supplied “off the shelf” by any reputable supplier, has a known wet gas flow performance that is accurately predicted by a freely available ISO published wet gas correlation.

Industry has more understanding of Venturi meter wet gas flow response than that stated in these ISO documents. In 2014 Graham et al [18] extended the work of Britton et al [17] on the influence on wet gas flow over-reading of Venturi meter flow orientation. A Venturi meter wet gas correlation for vertical up flow was offered by Graham et al. There are other published vertical up flow Venturi meter correlations, e.g. Xu et al [21]. There are also various ongoing academic and commercial programmes to model wet gas flow through a Venturi meter, e.g. van Werven M. et al [22] & Lupeau A et al [23]. Wet gas flow through Venturi meters has been, and still is, a highly researched important topic.

Industry has learned a lot about Venturi meters reaction to wet gas flow. The Venturi meter wet gas flow response is not just repeatable, but reproducible, and therefore very predictable. For ≥ 2” nominal meter size ISO offers a reliable horizontally installed Venturi meter wet gas correlation. With the exception of the orifice DP meter, industry has no equivalent detailed knowledge of any other gas meter’s reaction to wet gas flow.

4b Ultrasonic Meters Meter Wet Gas Response

The response of ultrasonic meters to wet gas flow has been sporadically researched by competing USM manufacturers over the last twenty years. One issue with understanding USM wet gas flow response is that unlike the orifice & Venturi meter there is no ‘standard’ design. Different USM manufacturers have different designs, some clamp-on, some integral meters, different number of paths, different locations of paths, different transducer designs and different software. This means any USM wet gas test result is only applicable to that particular meter design. This significantly hinders industries development of general USM wet gas flow performance understanding.

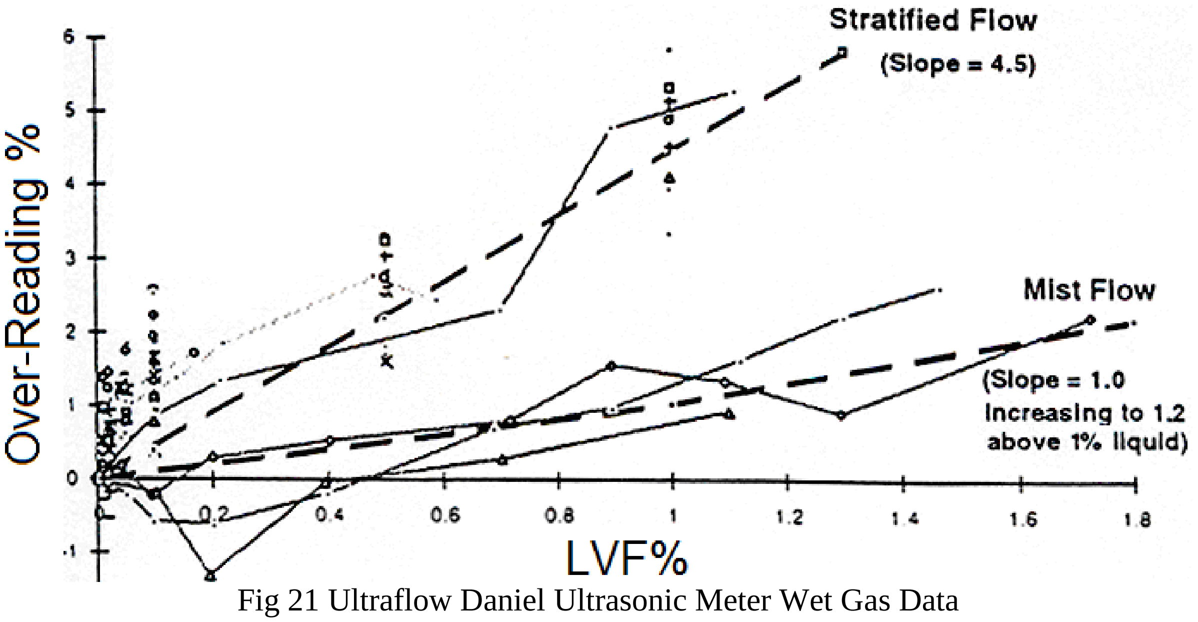

Fig 21 Ultraflow Daniel Ultrasonic Meter Wet Gas Data

In 1996 a Joint Industry Project (JIP) named ‘Ultraflow Wet Gas Development Project” conducted R&D into the wet gas response of the first generation Daniel senior sonic USM.

The results were summarized by Wilson [24]. The test series included NEL laboratory nitrogen / water tests and natural gas / condensate tests at UK gas terminals. The laboratory tests had stratified flows and the gas terminal flows were annular mist (or ‘mist’) flows. This consortium chose to use percentage LVF as the liquid loading parameter. With the stated laboratory and gas terminal fluids and stated flow conditions this converts to the stratified flow laboratory tests having a maximum Lockhart Martinelli parameter of approximately 0.04, and the mist flow terminal tests having a maximum Lockhart Martinelli parameter of approximately 0.14. That is, the tests covered up to about half the modern wet gas flow range of $X_{LM} \leq 0.3$.

The projects results are reproduced here in Figure 21. As with DP meters the different flow patterns through the 6” horizontally installed British Gas 4 path USM design produced different wet gas over-readings. The consortium fitted linear lines (i.e. correlations) to the two separate flow pattern data sets. There is some scatter in the data around the fits. There is not enough overall data, and not a high enough liquid loading to make any comprehensive conclusions. There is a noticeable relatively large scatter in over-reading at very low liquid loadings. There is a distinct change in response between stratified and mist flow. There is no data for the transitional flow pattern between stratified and mist flow, and in industry that is the most common horizontal flow pattern. In practice, even if the operator knows the gas is wet the operator does not easily know what flow pattern exists. A comprehensive wet gas correlation should account for not knowing the flow pattern. It is not ideal for the operator to have to know the flow pattern before choosing an appropriate correlation. Nevertheless, this initial research was interesting and useful, but unfortunately the USM manufacturers then stopped wet gas flow R&D and focused on other projects.

A 1998-2002 CEESI wet gas JIP investigated the response of various horizontally installed gas meters to wet gas flow. An **early** three bounce path Instromet USM design was tested (as shown in Figure 22). This USM design is significantly different to the meter in the Ultraflow tests. These results were released by the JIP in PowerPoint form in 2007. During these tests these natural gas with decane wet gas flow conditions were varied considerably to produce various flow patterns. Figure 23 shows the JIP data (where the y-axis ‘GMFR Corr’ is the over-reading ratio, OR). The meter tended to over-read the gas flow as the liquid loading increased up until a Lockhart Martinelli parameter of approximately 0.07. The over-reading had a lot of scatter. Beyond this liquid loading the meter response was random.

Fig 22. 3 Path USM During CEESI JIP.

At $X_{LM} < 0.07$ the radial position of installation had a significant effect on the over-reading. That is, how the USM paths are orientated relative to the wet gas flow pattern has a significant impact on how a USM reacts to wet gas flow. This is analogous with AGA 9’s recommendation that a USM for dry gas service needs to be calibrated with the flow conditioner fixed at one radial position so that no flow disturbance changes due to flow conditioner rotation can produce a flow rate prediction bias.

In 2011 Cameron presented a wet gas flow data set from a horizontally installed Cameron design 8”, 8 path USM at a Brazil Wet Gas Flow Measurement Workshop. Again, this data set is for a significantly different USM design than the two previous discussed wet gas data

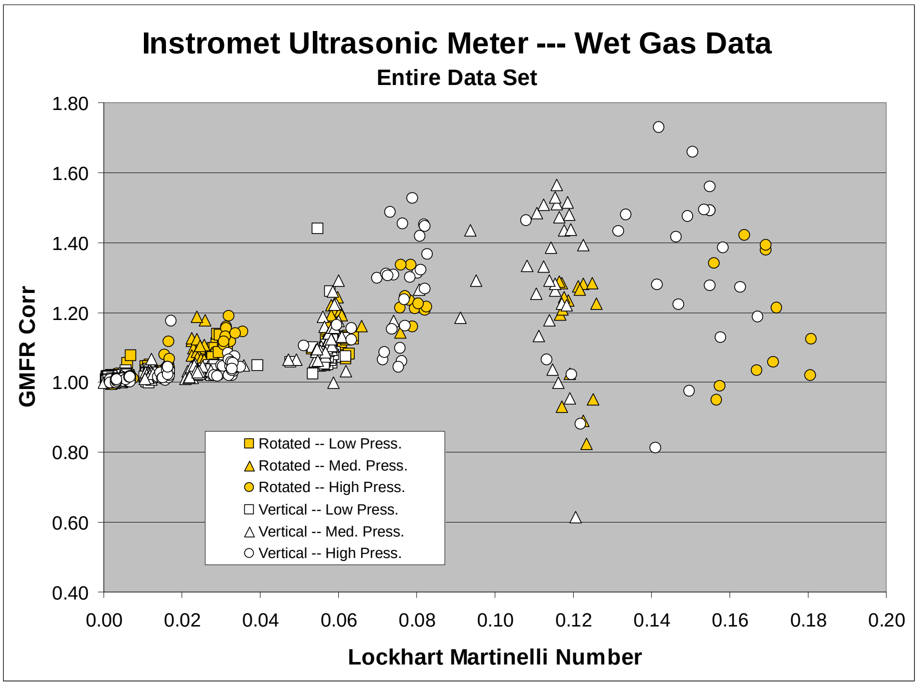

Fig 23. CEESI JIP 3 Path USM Wet Gas Flow Data

sets. This data was released in PowerPoint form only. Cameron chose to mainly show the data in terms of LVF%. It was stated that the data had Lockhart Martinelli parameters up to 0.3. Two Cameron graphs are reproduced here as Figure 24. The tests were conducted at 20 & 60 Bar. Due to limitations of the test facility used the maximum gas velocity was relatively low at 12 m/s. It is assumed by these authors that the fluids were Nitrogen and a light hydrocarbon (Exxsol D80).

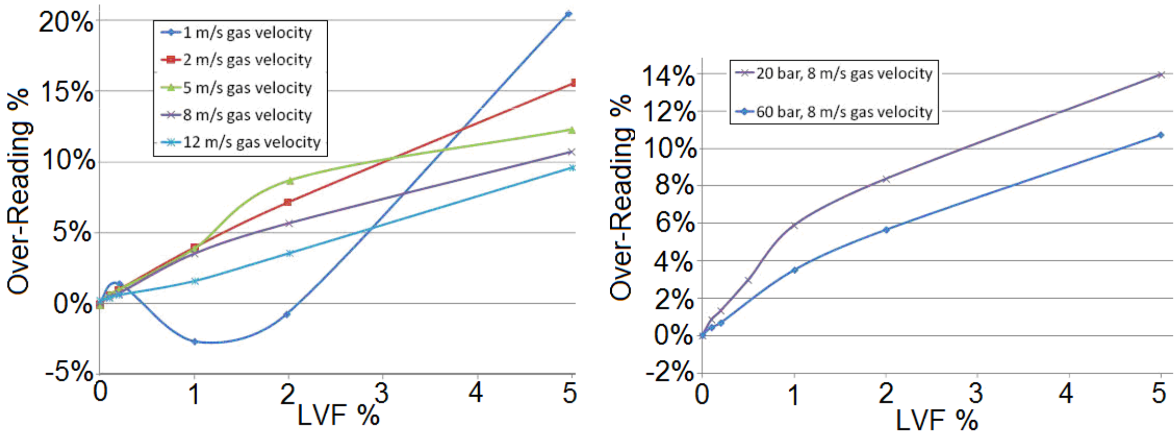

Fig 24. Cameron 8", 8 path USM Design Wet Gas Flow Data.

Figure 24's left hand graph shows 60 Bar data. There is a general over-reading but obvious significant scatter due to gas velocity / flow rate. There is no obvious gas velocity trend. Further analysis is hampered by the limited maximum gas flow rate of the data. Figure 24's right hand graph shows a possible pressure effect on the over-reading. However, this is an isolated data set. There are only two pressures, and no repeat tests. There is not enough data here to make any comprehensive statement on pressure effects. Figure 24 indicates that this 8" USM meter, while having good dry gas performance, does not have a particularly predictable wet gas bias. This is a similar issue to that seen in the Ultraflow data in Figure 21.

Fig 25. Clamp On Ultrasonic Meter Under 8” Wet Gas Flow Tests at CEESI

Fig 26. Integral Three Bounce Path Ultrasonic Under 8” Wet Gas Flow Tests at CEESI

In 2013 a 3rd party asked CEESI to wet gas flow test six meters in series. These were:

- an 8” schedule 40 (7.981”) clamp-on bounce path ultrasonic meter (see Fig 25),
- an 8” schedule 80 (7.625”) 3 bounce path ultrasonic meter (see Fig 26),
- an 8” schedule 80 chordal four path (Westinghouse) ultrasonic meter (see Fig 30),
- an 8” schedule 80, 0.6 beta Venturi meter (see Fig 15),
- a 6” schedule 80, 0.6 beta Venturi meter (see Fig 16), and
- an 8” schedule 40, 0.689 beta orifice meter (see Fig 12).

The data analysis of the three DP meters was included in section 4a. Table 4 shows the wet gas test range.

Parameter	CEESI Test Range
Pressure	17to 70 bara
Gas to liquid DR	0.016 < DR < 0.075
Fr_g range	0.5 < Frg < 3.2
X_{LM}	$0 \leq X_{LM} < 0.16$
Inlet Diameter	7.625” ≤ D ≤ 7.981”
Gas / Liquid phase	Gas /HCL/ Water

Table 4. CEESI 8” Multiple Flow Meter Wet Gas Flow Test Range.

The clamp-on ultrasonic meter (see Figure 25) had two sets of transducers each producing a bounce path. One path was a vertical path (with transducers installed at 12 o’clock) and the other was a horizontal path (with transducers installed at 3 o’clock). The vertical path was guaranteed to encounter the liquid regardless of the flow pattern. The horizontal path was likely to encounter some liquid for most wet gas flow conditions. The transducers supplied were not rated for the lowest pressures of the test and only data at a density ratio of 0.036 was recorded. The local 20D spool where the clamp-on meter was installed (at mid-stream on the spool) was schedule 40. There was an expansion / reduction 0.178” step between this spool and the neighbouring schedule 80 pipes. The possibility of some liquid hold up in this schedule 40 spool was discussed but considered unlikely as the gas velocities ranged between 5 & 15 m/s.

The dry gas response of the 8” clamp-on meter was good, it matched the facility reference meters to 1%. However, this clamp-on meter was severely affected by the presence of wet gas flow. Figure 27 shows the results. The significant gas flow rate prediction errors produced in the limited data set seem to be random. There was no discernible relationship between the over-reading and the Lockhart Martinelli parameter or gas densiometric Froude number.

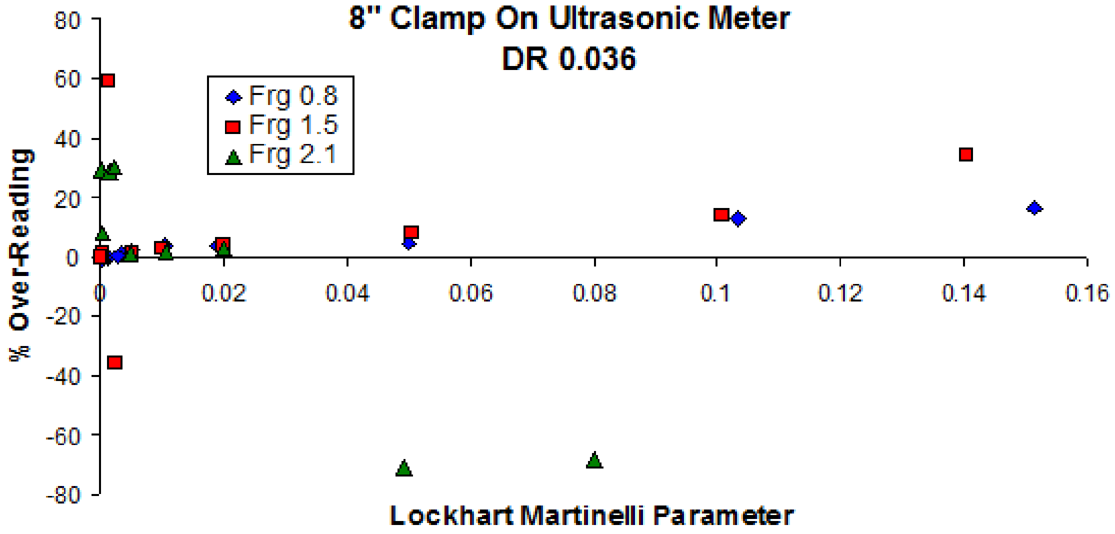

Fig 27. Data from 8” Clamp-On Bounce Path Ultrasonic Meter

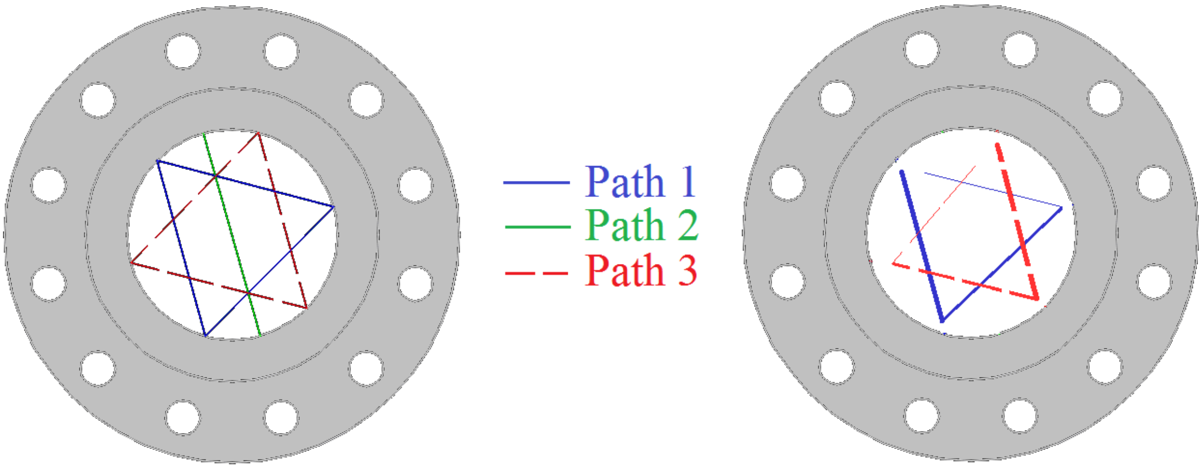

Fig 28. Sketch of the Three Bounce Path Ultrasonic Meter Tested at CEESI.

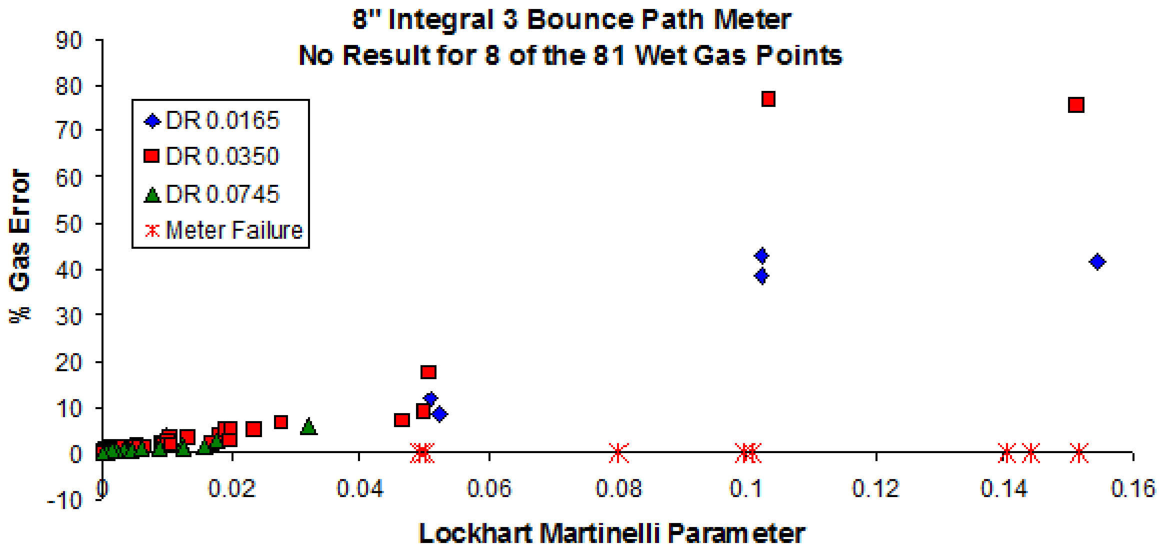

Fig 29. Data from 8”, Three Bounce Path Ultrasonic Meter.

The 8”, three bounce path ultrasonic meter tested had two double bounce paths (paths 1 & 3) and one single bounce path (path 2). A sketch of these paths is given in Figure 28. The left hand sketch shows the relative position of the paths, although the transducers are spaced axially along the meter body. The right hand side of Figure 28 attempts to show the axial nature of paths 1 & 3. The meter shown in Figure 26 is installed (as per design) such that the single bounce path is positioned close to (but not at) the vertical 12 to 6 o’clock plane.

The bounce path ultrasonic meter design is (like all ultrasonic & DP meters) inherently a single phase meter. The bounce path concept has pros and cons when compared against other common single phase gas ultrasonic meters. In the baseline single phase performance checks this meter had a good performance, matching the facility reference gas flow rate to < 1%. However, when used in the highly adverse and specialized case of wet gas flow each bounce path’s coverage of the pipe area almost guarantees that each path will encounter the liquid regardless of the flow pattern. With ***every*** path adversely affected by the presence of liquid wet gas presents a challenge to this meter. The test results show that this is the case.

The bounce path ultrasonic meter was severely affected by the presence of wet gas flow. Figure 29 shows the results. For eight of the eighty six wet gas data points (approximately 9% of the data) this meter failed to produce a gas flow rate prediction[2]. The failures began to appear at $X_{LM} \geq 0.05$. Of the seventy eight test points where the meter gave a gas flow rate prediction there was significant scatter. The significant gas flow rate prediction errors produced seem to be random. There is a rough relationship between increasing liquid loading and increasing ‘over-reading’ (and unfortunately meter failure), but no discernible relationship between the over-reading and the gas to liquid density ratio or gas densiometric Froude number.

Fig 30. 8” Four Chordal Path Ultrasonic Meter at the CEESI Wet Gas Test Facility

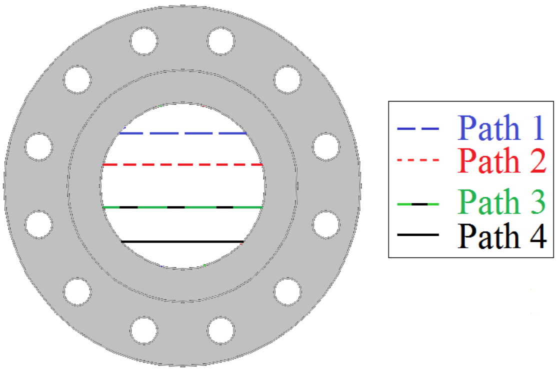

Fig 31. Sketch of a Four Chordal Path Ultrasonic Meter (not to scale)

Figure 30 shows the 8” chordal four path (Westinghouse design) ultrasonic meter installed in the CEESI wet gas test facility. Figure 31 is a sketch of the path orientation. Each path is at a set height in the horizontally installed meter body. Hence, for wet gas flows, the lower the path (i.e. the higher the path #) the more likely it will encounter higher liquid concentrations.

As expected the 8” chordal four path ultrasonic meter was found to have a good dry gas baseline performance, matching the facility reference gas flow rate to < 1%. This meter was adversely affected by the presence of wet gas flow. Figure 32 shows the meter performance.

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[2] For the 9% of wet gas flow conditions where the bounce path ultrasonic meter did not produce a useable output the meter did not ‘fail’ as such, but produced huge over-readings in the order of > 6e6%. This obviously erroneous result is effectively a ‘no result’.

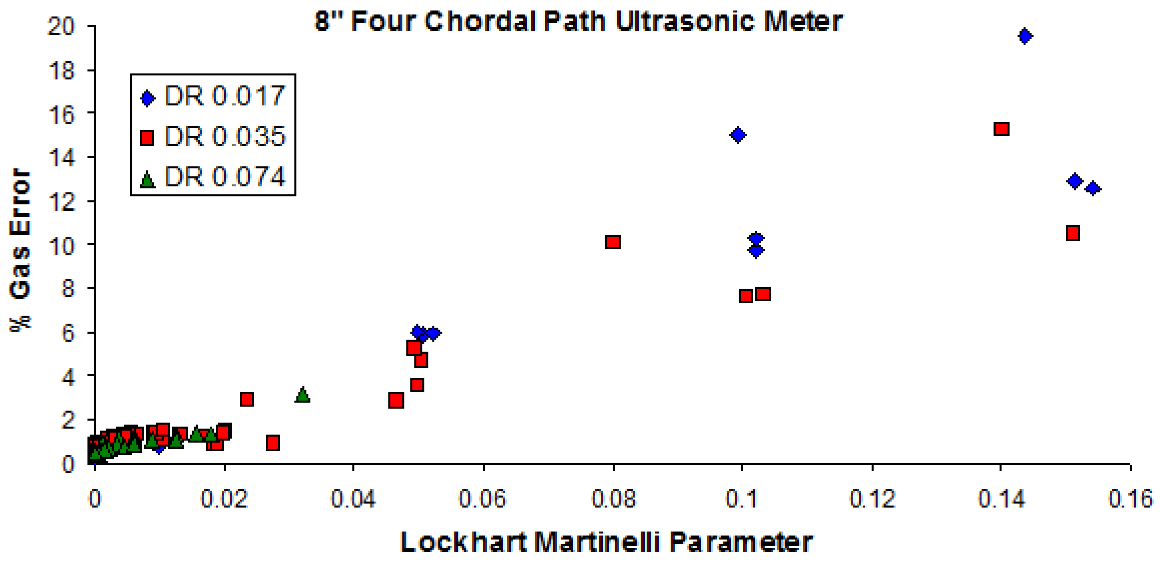

Fig 32. Data from 8”, 4 Chordal Path Ultrasonic Meter.

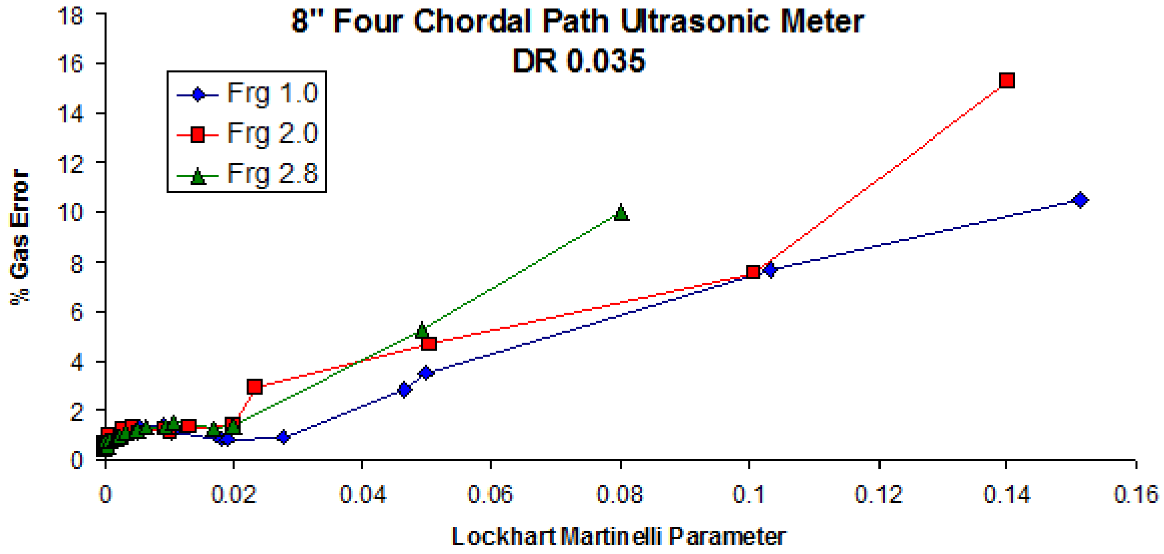

Fig 33. Data from 8”, 4 Chordal Path Ultrasonic Meter.

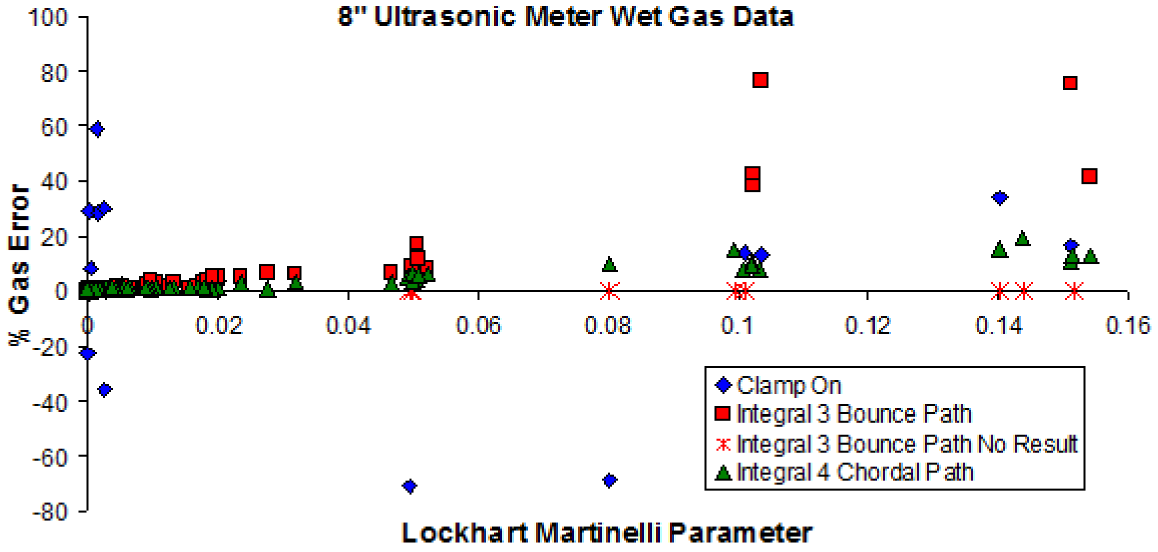

Fig 34. Comparison of Clamp-On, Bounce Path & Chordal Ultrasonic Meter Wet Gas Results

There is a general relationship between increasing liquid loading and increasing gas flow rate error (or 'over-reading'), however there is considerable scatter in the percentage Over-Reading vs. Lockhart Martinelli Parameter relationship. Figures 32 & 33 do not show any clear evidence of gas to liquid density ratio or gas densiometric Froude number effects.

Figure 34 shows the performance of the three different 8" ultrasonic meter designs when they were tested together at CEESI. The 8" chordal four path ultrasonic meter data has less scatter than the other ultrasonic meter designs data and it also tends to have lower over-readings. This may be due to the upper paths of the chordal design tending to encounter less liquid than the lower paths, or the paths in the other ultrasonic meter designs, and therefore this meter design has the benefit of some partially operational paths. (For all but the most extreme pressures and flow rates gravity dictates that even with annular mist flow in horizontal installations there is a liquid density gradient, i.e. more liquid concentrated at the base of the pipe / meter body.) The results shown in Figure 32 & 33 are similar to the results released independently by Cameron for their chordal meter (see Fig 24).

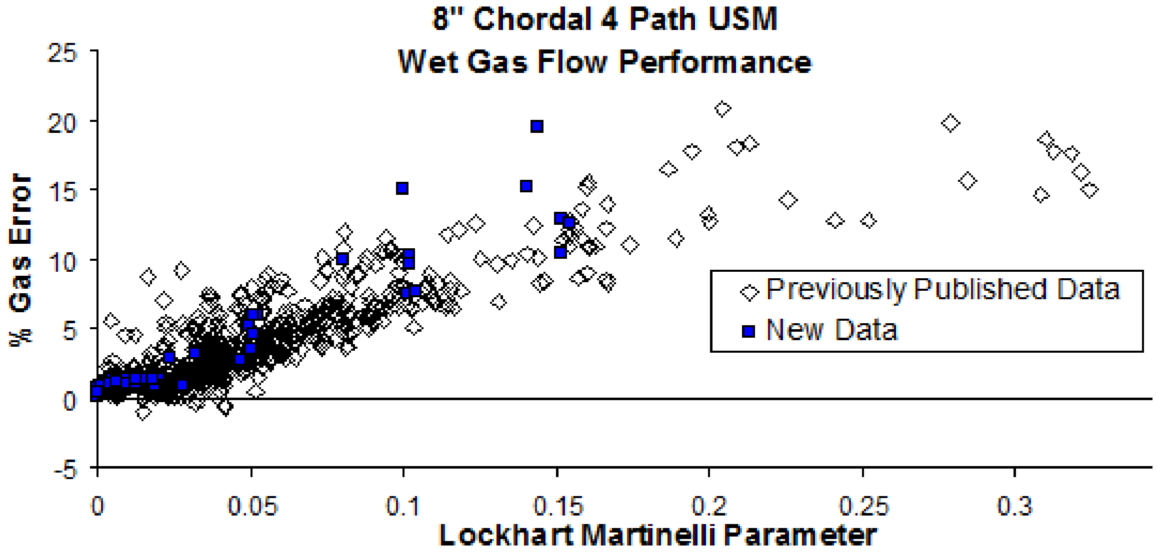

Fig 35. Massed Wet Gas Data from 8", Chordal Four Path Ultrasonic Meter.

The smaller scatter and lower wet gas over-reading of the chordal 4 path ultrasonic meter is relative to the performance of the other ultrasonic meters. To review the performance in a wider context it is necessary to compare the result to other wet gas results from the same meter (to check for repeatability) and to compare the response to the DP meter. Figure 35 compares the 8" chordal path meter's performance in these ultrasonic meter comparison tests to its previous performance when it was resident in the CEESI wet gas flow facility downstream of various 3rd party equipment tests. The new data is within the wet gas flow condition range of the previous massed data set, however, clearly there is some scatter in the chordal path ultrasonic meter wet gas response.

There is a 4" chordal 4 path ultrasonic meter resident in the CEESI 4" multiphase wet gas flow test facility. This meter is the same design as the 8" chordal 4 path ultrasonic meter being discussed here. These 4" & 8" meter have been tested over similar wet gas flow conditions. Figure 36 compares all the 8" chordal 4 path ultrasonic meter data shown in Figure 35 to a wet gas data set from the 4" meter of the same design. Clearly, at higher Lockhart Martinelli parameters (i.e. higher liquid loading) there is a significant difference in over-reading between the 4" & 8" meters. This infers it may not be possible to create a correction factor for one size of ultrasonic meter and expect it to work on another size.

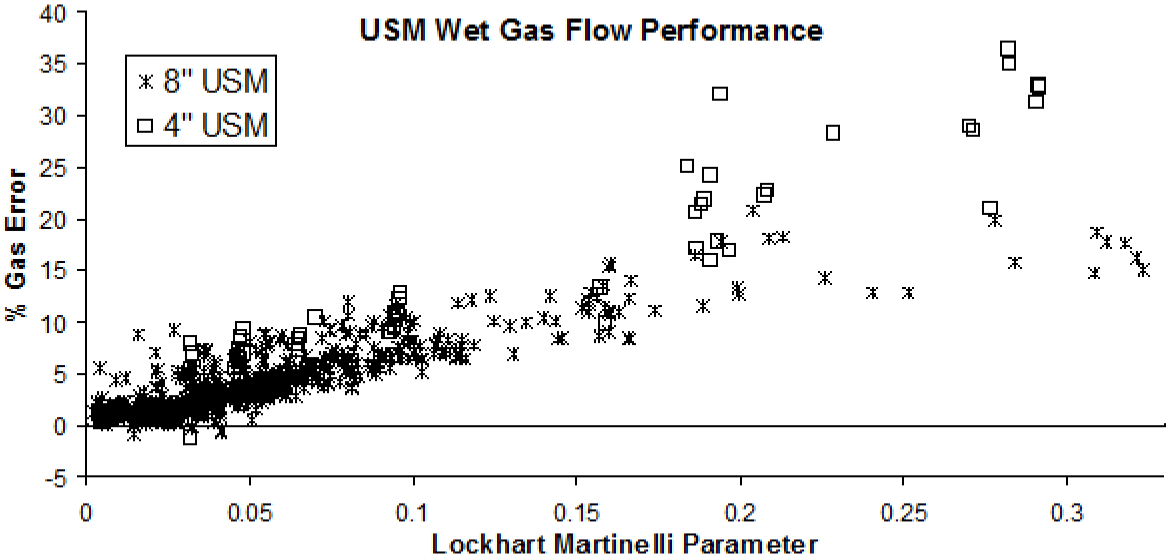

Fig 36. Massed Wet Gas Data from 8", Chordal Four Path Ultrasonic Meter.

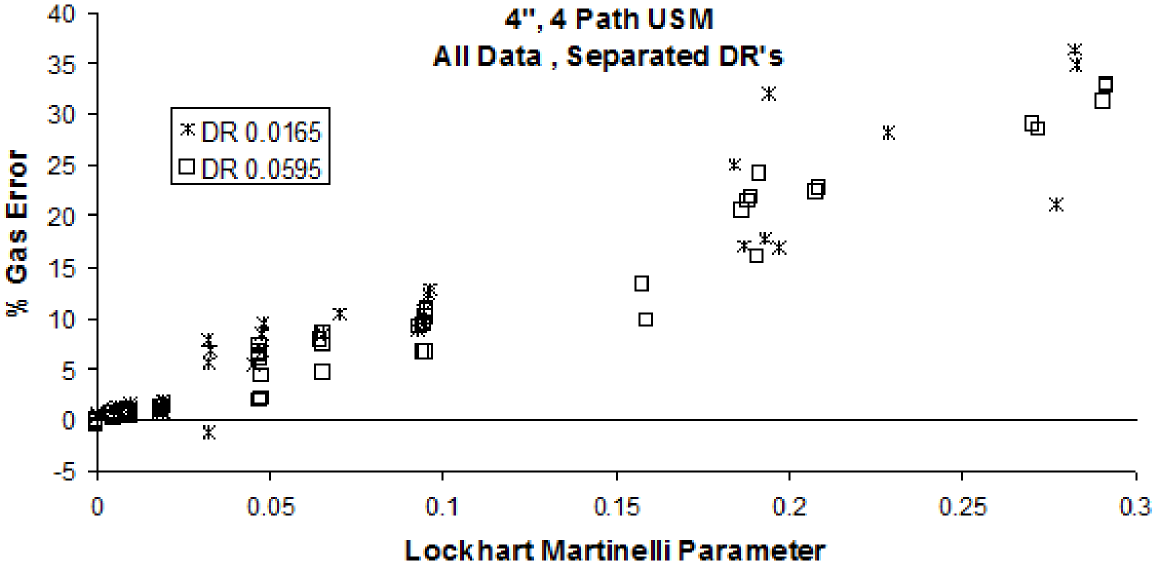

Fig 37. 4" Chordal 4 Path Data Set, Separated Density Ratio.

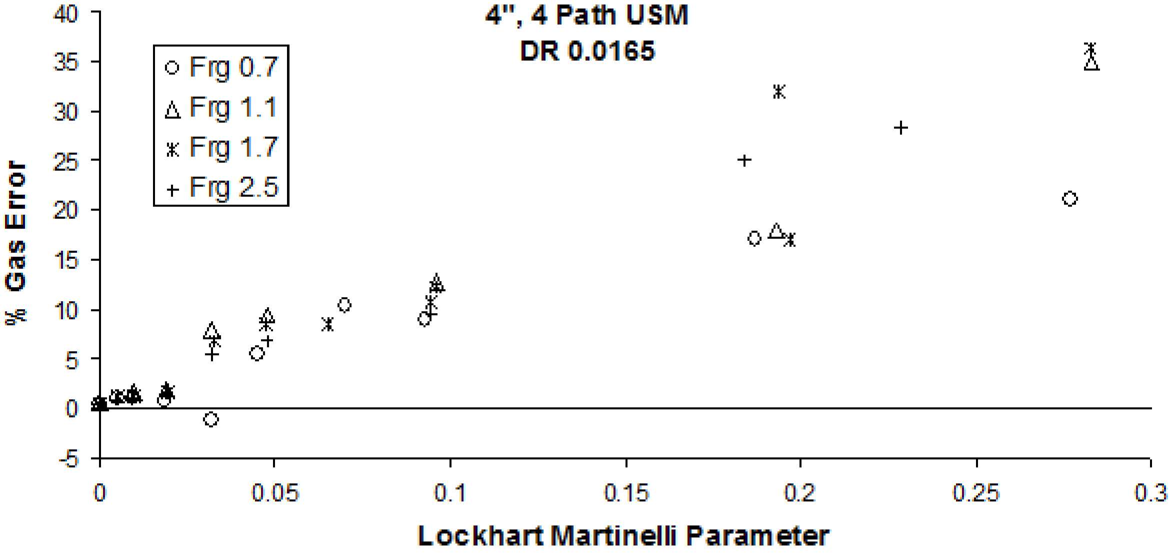

Fig 38. 4" Chordal 4 Path Data Set, Set DR, Separated Fr_g.

With the exception of the higher over-reading at higher Lockhart Martinelli parameters, the wet gas performance of the 4” chordal 4 path ultrasonic meter was similar to the 8” meter. The 4” chordal 4 path ultrasonic meter showed a general relationship between increasing liquid loading and increasing over-reading. This is shown in Figure 37. However, again, there was considerable scatter in the percentage Over-Reading vs. Lockhart Martinelli Parameter relationship. Figures 37 & 38 suggest this scatter cannot be accounted for due to any gas to liquid density ratio or gas densiometric Froude number effects.

No standards board (or ultrasonic meter manufacturer) has yet published any comprehensive ultrasonic meter wet gas correlation. The DP meter is the only gas meter design type known to have a reproducible wet gas response and therefore a corresponding ISO correlation.

5. DP Meter & Ultrasonic Meter Wet Gas Response Comparisons

There is commercial pressure to compare Ultrasonic & DP meter wet gas flow performance.

A sample comparison of the 8” chordal four path ultrasonic & Venturi meters that where installed in series in the CEESI multiphase wet gas facility (see Figures 30 & 15 respectively) is shown in Figure 39. Both meters have significant wet gas over-readings. The ultrasonic meter over-reading tends to be smaller than that of the Venturi meter but this is a relative term. Both have substantial gas flow rate errors. In most applications such an error will need to be corrected, and hence it is not the comparison of the uncorrected over-reading that is of importance, but the availability and performance of respective wet gas correlations. The ‘off the shelf’ ISO compliant Venturi meter has the ISO TR 11583 Venturi meter correlation available. For a known liquid flow rate the result of applying the Venturi meter correlation is included in Figure 39. The gas flow rate prediction error after applying the ISO correlation is within the ISO stated correlation uncertainty. There are no standards board or manufacturer produced published USM wet gas correlations. Therefore unlike the Venturi meter there is no ultrasonic meter wet gas correlation with which to correct this ultrasonic meter’s over-reading.

A sample comparison of the 8” chordal four path ultrasonic & orifice meters that where installed in series in the CEESI multiphase wet gas facility (see Figures 30 & 12 respectively) is shown in Figure 40. Both meters have significant wet gas over-readings. The ultrasonic meter over-reading tends to be slightly smaller than that of the orifice meter but both have substantial gas flow rate errors. Again, in most applications such an error will need to be corrected, and hence it is not the comparison of the uncorrected over-reading that is of importance, but the availability and performance of respective wet gas correlations. The ‘off the shelf’ ISO compliant orifice meter has the ISO TR 12748 orifice meter correlation available. This correlation is technically only for orifice meters ≤ 4” in diameter, but in industry this correlation can and will be extrapolated to larger orifice meters. For a known liquid flow rate the result of applying this orifice meter correlation is included in Figure 40. The gas flow rate prediction error after applying the ISO correlation was found to be -2% to +3% to 95% confidence. There are no standards board or manufacturer produced published USM wet gas correlations. Therefore unlike the orifice meter there is no ultrasonic meter wet gas correlation with which to correct this ultrasonic meter’s over-reading.

When a gas meter is used for low liquid loading wet gas flows the operator may choose to ignore that the gas flow is not dry and hope that the over-reading is negligible. In such a scenario the gas meter design with the lowest over-reading would be desirable. Figures 39 & 40 have circled the wet gas liquid loading region of interest in such a scenario. The chordal 4 path ultrasonic meter generally has a lower over-reading than the Venturi meter but the

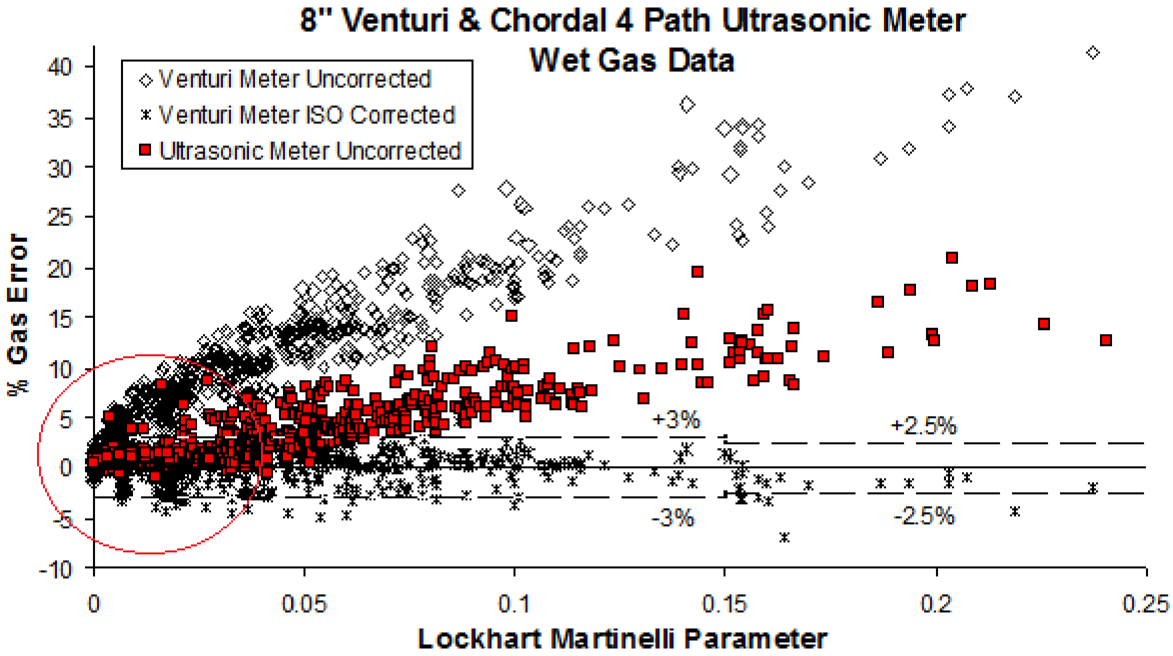

Fig 39. 8” Venturi & Chordal 4 Path Ultrasonic Meter Wet Gas Data Comparisons.

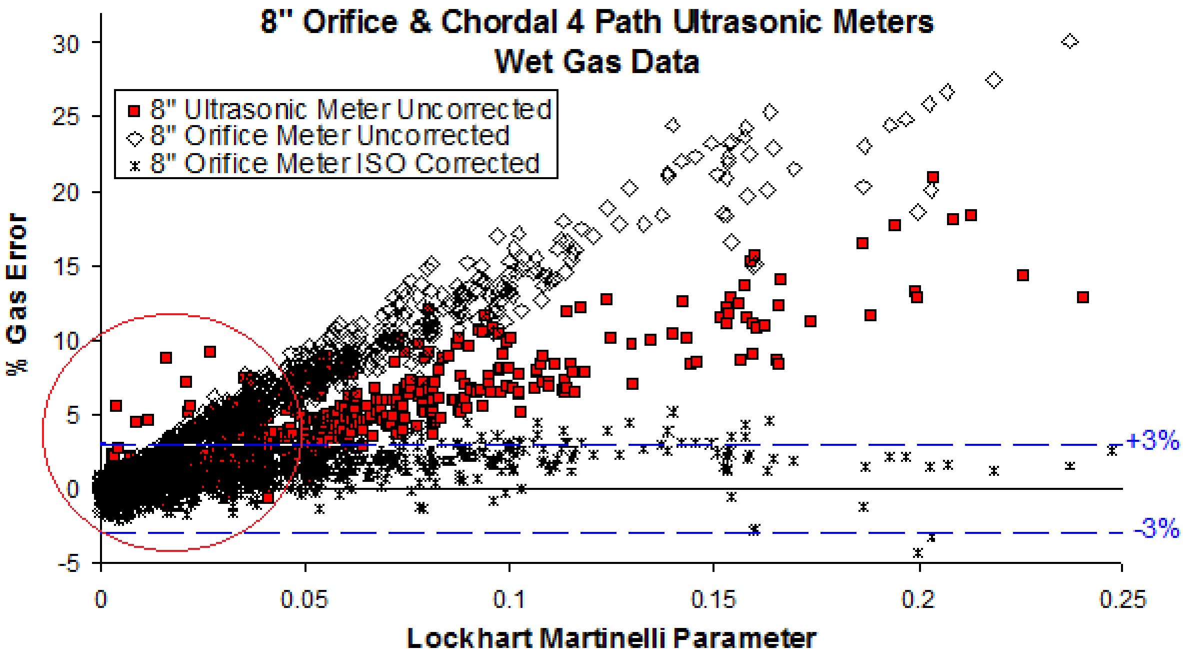

Fig 40. 8” Orifice & Chordal 4 Path Ultrasonic Meter Wet Gas Data Comparisons.

significantly higher level of ultrasonic meter scatter negates any significant advantage in this respect. The ultrasonic meter can’t be guaranteed to have a lower over-reading in this liquid loading region. Figure 41 highlights the wet gas over-reading comparison of the 8” orifice & chordal 4 path ultrasonic meter at $X_{LM} \leq 0.05$. The difference in over-reading between the orifice and ultrasonic meter is more marginal than between the Venturi and ultrasonic meter. Again, the ultrasonic meter can’t be guaranteed to have a lower over-reading in this liquid loading region.

These comparisons of the wet gas flow performance of 8” orifice, Venturi and chordal 4 path ultrasonic meters have also been made with 4” meters. The results and conclusions made on the 8” data are substantiated by the 4” data. Figure 42 shows sample CEESI 4” data.

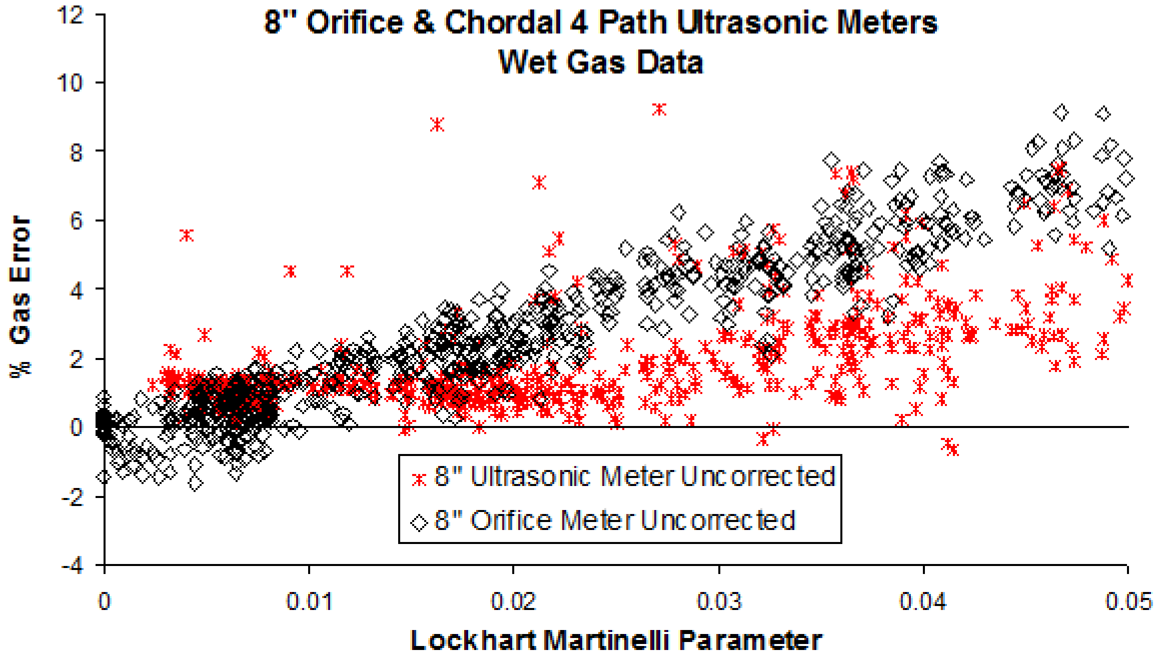

Fig 41. 8” Orifice & Chordal 4 Path Ultrasonic Meter Performance at Low Liquid Loading.

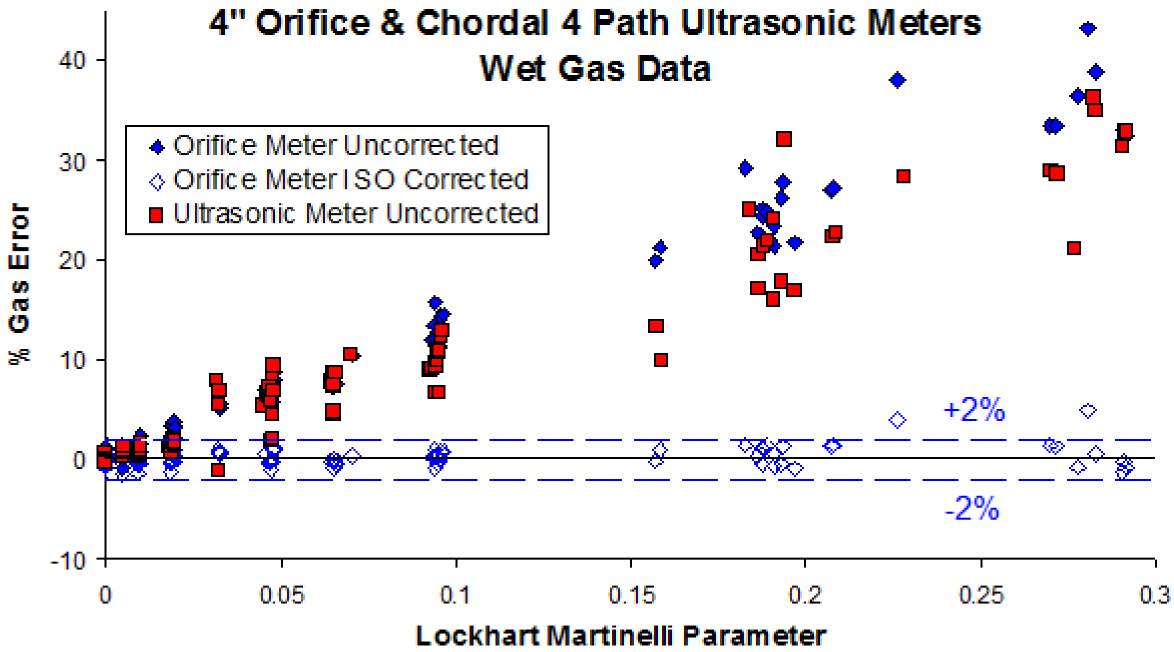

Fig 42. 4” Orifice & Chordal 4 Path Ultrasonic Meter Wet Gas Data Comparisons.

Figure 42 compares the performance of 4” orifice and chordal 4 path ultrasonic meters. Again, there is no advantage between using the two type of meters at low liquid loading (with no correction applied). Again, the ISO complaint 4” orifice meter had the ISO correlation available, whereas there is no available ultrasonic meter correlation.

In some applications the operator may not know if the gas is wet. Even if wet gas flow is confirmed, all gas meters with a wet gas correlation require the liquid flow rate (or some liquid loading parameter) supplied from an external source. The common methods (e.g. test separator history or tracer dilution techniques) are spot checks. In these cases the operator is blind to changing liquid loadings and blind to the associated gas flow rate prediction bias between these periodic checks. Therefore, a wet gas monitoring system internal to the meter is desirable.

It has been suggested by some that the ultrasonic meter has an advantage over DP meters in wet gas flow service on the grounds that the ultrasonic meter has a comprehensive diagnostic system that could be used to show changes in liquid loading. It is inherently inferred in these statements that the DP meter has no diagnostic capabilities, and no method of monitoring liquid loading. However, this is not correct. The Venturi meter has a very well established widely used liquid loading monitoring system, and the generic DP meter now also has a comprehensively proven diagnostic system. Hence, the Venturi, orifice and any generic DP meter does have the capability to monitor changes on liquid loading.

6. Liquid Loading Monitoring

6a. DP Meter Liquid Loading Monitoring

In 1997 de Leeuw [9] showed that the ratio of a Venturi meter's permanent pressure loss (PPL, DP_{PPL}) to the traditional DP (DP_t), often called the Pressure Loss Ratio, or 'PLR', was a fixed value for a given Venturi meter geometry with single phase flow. This is confirmed for orifice & Venturi meters by ISO 5167 Part 2 and Part 4. De Leeuw then showed that the PLR of a Venturi meter was sensitive to wet gas liquid loading, and hence monitoring the PLR gives a very simple, effective and reliable Venturi meter liquid loading monitor.

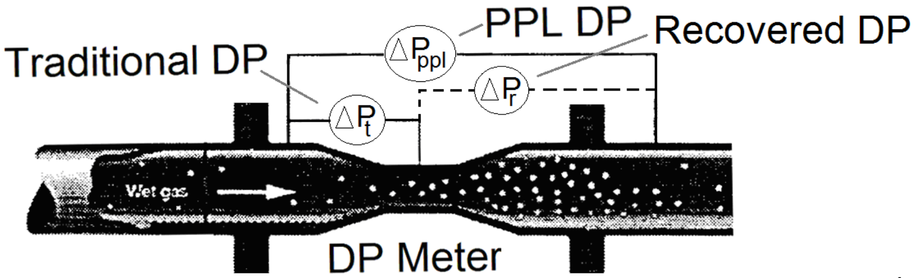

Fig 43. Modified De Leeuw Sketch Showing DP Readings.

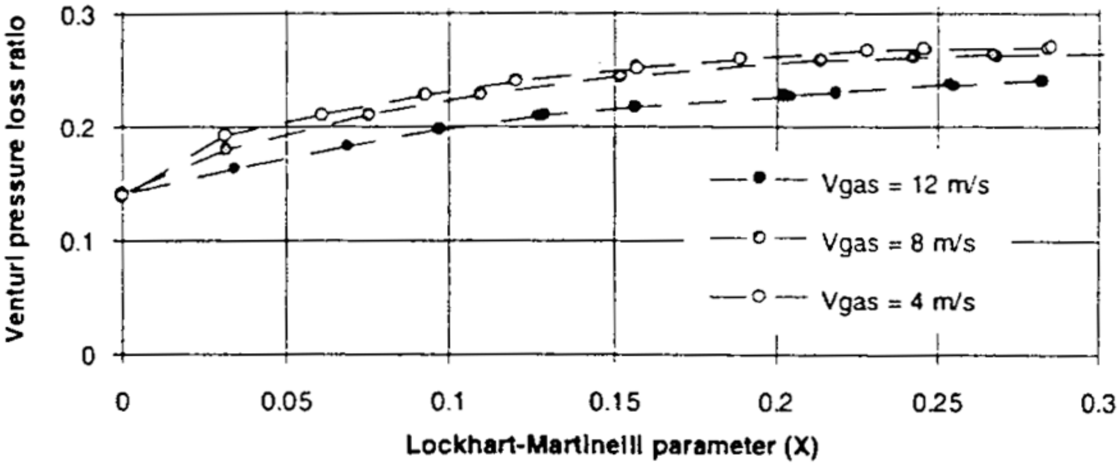

Fig 44. De Leeuw 4", 0.4β Venturi Meter Wet Gas PLR vs. X_{LM} Wet Gas Data.

Figure 43 shows a modified de Leeuw [9] sketch of the Venturi meter with the traditional & PPL DPs required to read the PLR. Figure 43 also shows a later general DP meter diagnostic development of also reading the recovered DP (DP_r), as described by Steven et al [20, 27] & Rabone et al [25] & [26]. Figure 44 shows de Leeuw sample wet gas data showing the PLR vs. X_{LM} relationship.

This de Leeuw technique has spawned multiple wet gas meter products. The Expro 'SmartVent', the Solartron Dualstream I, the ABB & Krohne wet gas Venturi meters etc. use this technique to meter the gas and liquid flow rates without liquid loading information being required from an external source. At present there are no equivalent ultrasonic meter technology based wet gas meter products. Furthermore, ISO TR 11583 [1] describes this PLR vs. X_{LM} wet gas metering technique for Venturi meters. ISO TR 11583 even includes some approximate predictions for predicting the gas & liquid flow rates via combining the information from the standard meter and the PLR measurement for some Venturi meter geometries. (Further discussion of this ISO prediction is outside the scope of this paper.)

This concept is applicable to all generic DP meters. The orifice meters photographed in Figures 9 & 12 have a downstream tap for this liquid monitoring capability, as do all the Venturi meters in Figures 15 thru 18. Any DP meter operator can monitor for liquid loading changes via PLR changes. An operator can do this manually, or there are software packages available, e.g., the patented comprehensive DP meter diagnostic system 'Prognosis' (see Steven et al [20, 27] & Rabone et al [25]) has software that among other capabilities includes this liquid loading monitoring capability. Prognosis also includes further dynamic pressure field monitoring techniques that can further diagnose wet gas as the source of the diagnostic alarm (see Rabone et al [26]). Steven [27] showed that while an orifice meters PLR parameter can be used to monitor liquid loading, for an orifice meter in particular, the ratio of the recovered to PPL DPs (or 'RPR') is more sensitive to liquid loading than the PLR. The Prognosis software includes this RPR check (see Rabone [26]) as well as DP stability monitoring to produce a 'wet gas flow' monitoring system.

6b. Chordal 4 Path Ultrasonic Meter Liquid Loading Monitoring

Most ultrasonic meters have a generic comprehensive diagnostic system consisting of the following diagnostic checks: Speed of Sound, Path Velocity Ratios (usually shown individually as well as split into Profile Factor & Symmetry information), Path Performance, Path Turbulence, Path Signal to Noise Ratio and Path Gain. Different manufacturers have their own methods of displaying these diagnostics. The diagnostic result, i.e. "diagnostic pattern", produced by cross referencing these seven diagnostics is said to indicate wet gas flow. Different manufacturer displays will of course produce different patterns.

There is significantly less literature regarding the generic ultrasonic meter diagnostic system's reaction to wet gas flow than there is for a generic DP meters wet gas monitoring system. This is in part because industry has released significantly less wet gas flow R&D on ultrasonic meters than DP meters. Another hindrance to understanding ultrasonic meter wet gas flow response is the variation of ultrasonic meter and diagnostic display designs. Test data from one ultrasonic meter design is not automatically transferable to other designs. Furthermore, physically similar ultrasonic meter designs (such as two competing chordal 4 path designs) may have similar diagnostic responses to wet gas flow, but due to difference's in the diagnostic display the response may not be obviously similar.

Lansing [28] gives a short discussion on one horizontally installed 4", chordal 4 path ultrasonic meter's diagnostic reaction to wet gas flow. Lansing says "…there are four basic diagnostic parameter that can be used to identify when liquids are present. They are Performance, Path Ratios, Path Speed of Sound and Turbulence values." Figures 45 thru 56 reproduces the Lansing graphs. No pressure or fluid type information was given. The liquid loading is shown as GVF%. The relationship of the GVF% to Lockhart Martinelli Parameter is shown by equation 8.

$$GVF\% = \left\{ \frac{\sqrt{\frac{\rho_l}{\rho_g}}}{X_{LM} + \sqrt{\frac{\rho_l}{\rho_g}}} \right\} * 100\% \qquad (8)$$

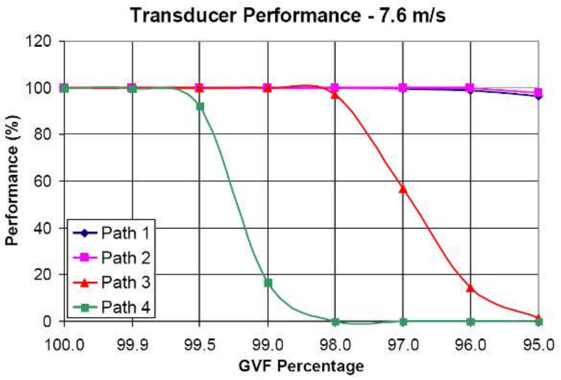

Fig 45. USM Performance vs. GVF%.

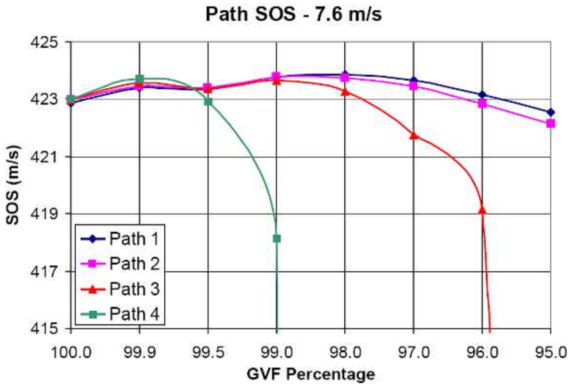

Fig 46. USM Speed of Sound vs. GVF%

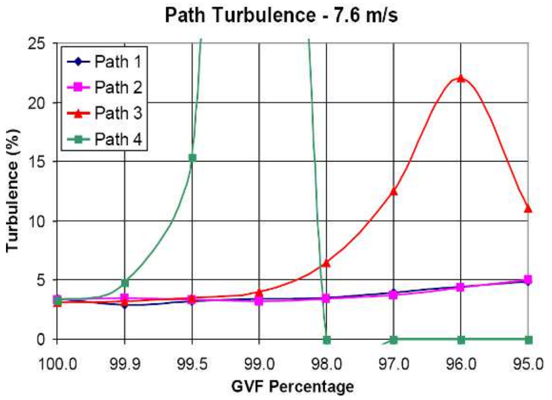

Fig 47. USM Turbulence vs. GVF%.

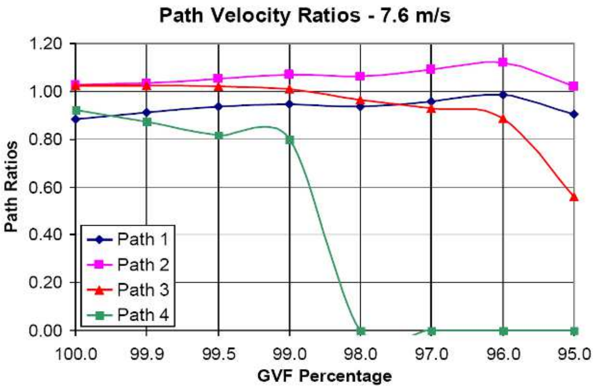

Fig 48. Path Velocity Ratios vs GVF%.

The horizontal flow pattern can place different amounts of liquid across each path thereby making each paths reaction to the wet gas flow potentially different. Figs 45 thru 48 have an unusual non-linear scale, i.e. unit lengths along the x-axis do not represent unit steps in GVF%. It is important to realise that Figs 45 thru 48 shows post test analysis. The standard ultrasonic meter diagnostic suites do not plot the diagnostic parameters vs. GVF% (or alternative liquid loading). In practice the operator will have to decipher the meaning of the generic ultrasonic meter diagnostic suite output from the standard USM diagnostic output display only.

Figure 45 shows that the lowest path (Path 4), which will experience the highest concentration of liquid with most flow patterns, begins to show performance abnormalities at a GVF of about 99.5%. Path 3 shows a similar problem at GVF < 98%. Figure 46 shows Path 4 beginning to show Speed of Sound (SOS) abnormalities at a GVF of about 99.5%. Path 3 shows a similar problem at GVF < 98%. Figure 47 shows Path 4 beginning to show turbulence abnormalities at a GVF < 99.9%. Path 3 shows a similar problem at GVF < 98%. Figure 48 shows Path 4 beginning to 'show' velocity abnormalities at GVF < 99.5%.

In field operation the ultrasonic diagnostic display shows this result in terms of Path Velocity Ratios, as reproduced here as Figures 49 to 52. It is difficult for an operator to judge from these path velocity ratio plots if the diagnostics are suggesting the flow is dry or wet (or has another problem). A better analysis is to use this information to plot Profile Factor (PF) vs. Symmetry. This is reproduced as Figures 53 thru 56. These plots identify an abnormality in the expected dry gas response somewhere between 99.9% < GVF < 99.5%. Unfortunately, with no gas to liquid density ratio information supplied it is not possible to convert this example to Lockhart Martinelli parameter terms.

In summary, this reproduced example (Lansing [28]) suggests that the ultrasonic diagnostic system starts to show an unspecified problem with Path 4 failing between 99.9% < GVF < 99.5%. Wet gas flow is one of several possible problems that could cause Path 4 to fail. When Path 3 also starts to show similar problems at GVF < 98% pattern recognition (by an experienced ultrasonic meter operator closely monitoring the diagnostics) can then potentially indicate wet gas flow as the likely problem.

The following example shows a direct comparison of the diagnostic / wet gas monitoring systems of the respective 8” chordal 4 path ultrasonic, orifice & Venturi meters. A sample mid wet gas flow condition has been selected for when these meters were tested in series.

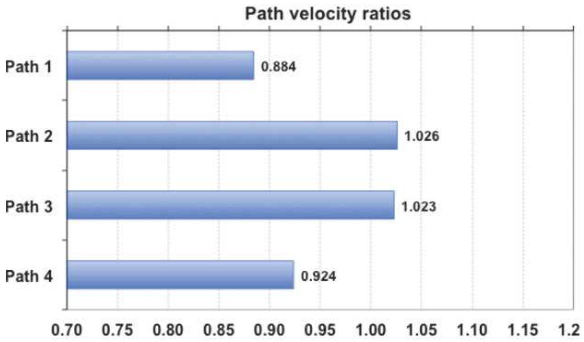

Fig 49. Path Velocity Ratios at 100% GVF

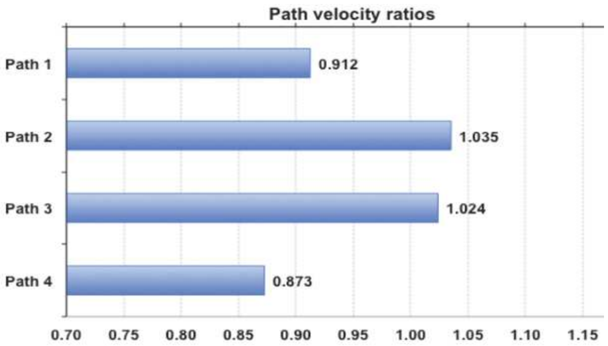

Fig 50. Path Velocity Ratios at 99.9% GVF

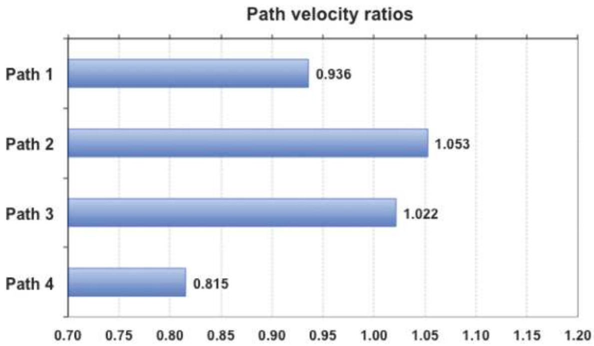

Fig 51. Path Velocity Ratios at 99.5% GVF

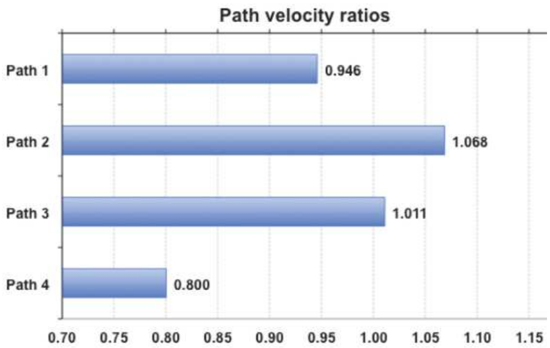

Fig 52. Path Velocity Ratios at 99.0% GVF

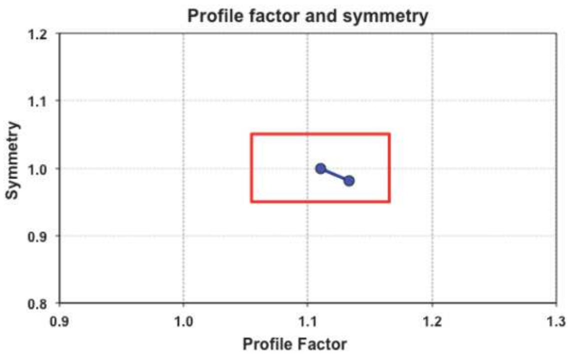

Fig 53. PF vs. Symmetry 100% GVF

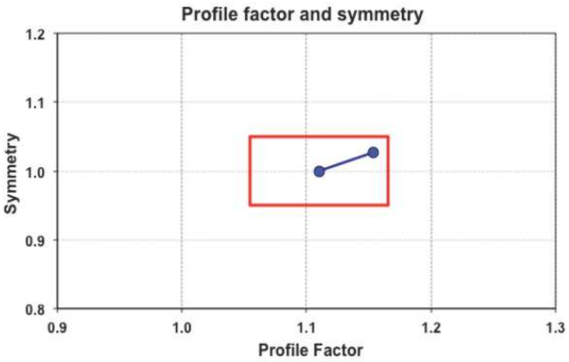

Fig 54. PF vs. Symmetry 99.9% GVF

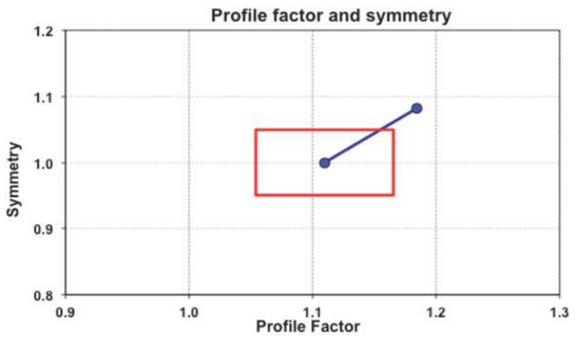

Fig 55. PF vs. Symmetry 99.5% GVF

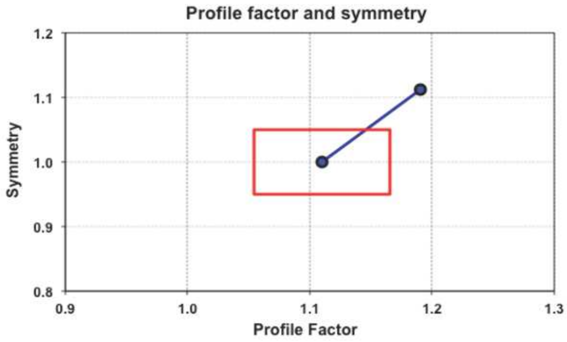

Fig 56. PF vs. Symmetry 99.0% GVF

6c. <u>CEESI 8” DP Meter & USM Wet Gas Monitoring Example</u>

Natural gas & Exxsol D80 (a light LHC) at a nominal 47 Bar(a), 35^0C flowed at 15.7 kg/s. The gas to liquid density ratio was 0.045 and the gas densiometric Froude number was 2.2. The GVF% & Lockhart Martinelli parameter range is shown in Table 5.

GVF %	100	99.87	99.64	99.33	98.89	98.53
Xlm	0	0.006	0.017	0.032	0.053	0.070

Table 5. GVF% vs. Lockhart Martinelli Parameter.

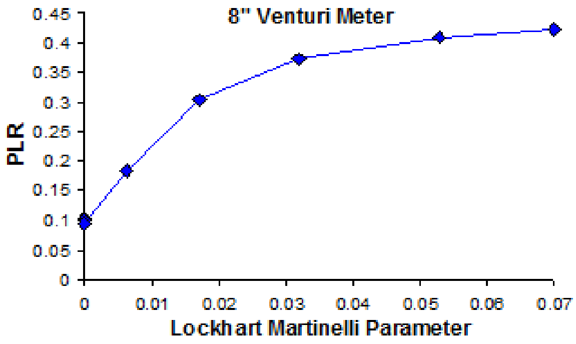

Fig 57. 8” Venturi Meter PLR vs. X_{LM}
Gas / LHC, DR 0.045, Fr_g 2.2.

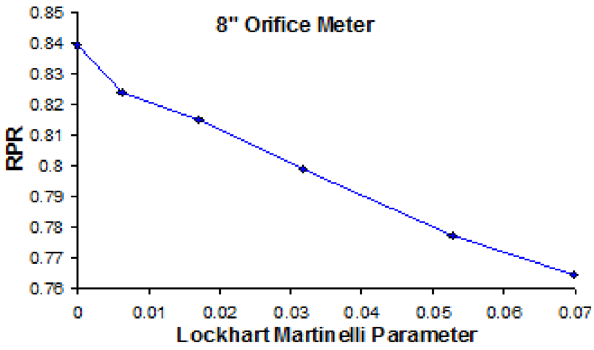

Fig 58. 8” Orifice Meter RPR vs. X_{LM}
Gas / LHC, DR 0.045, Fr_g 2.2.

Figure 57 shows the wet gas response of the 8”, 0.6β Venturi meter’s PLR vs. X_{LM}. The Venturi meter PLR is very sensitive to wet gas. Trending a Venturi meters PLR is a simple yet reliable and well established method for monitoring even small changes in wet gas liquid loading. Figure 58 shows the wet gas response of the 8”, 0.689β orifice meter’s RPR vs. X_{LM}. The orifice meter RPR is moderately sensitive to wet gas. Although less sensitive to liquid loading than the Venturi meters PLR, trending an orifice meters RPR is a simple and reliable method for monitoring for moderate liquid loading changes. As the DP ratio reading uncertainty is typically < 1% the Venturi meter can ‘see’ wet gas at $X_{LM} < 0.002$, while this orifice meter has a more modest identification threshold of $X_{LM} < 0.01$[3].

Figure 59 shows the ultrasonic meter individual path performance vs. liquid loading. Path 4 begins to show an abnormality from normal dry gas flow performance at a liquid loading

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[3] Only a few DP meter malfunctions cause the PLR & RPR values to drift in these particular directions. None of these other malfunctions have the associated DP fluctuations caused by wet gas flow. Hence, these DP meters monitoring systems can identify wet gas flow as the ***specific*** problem (see Rabone [26]).

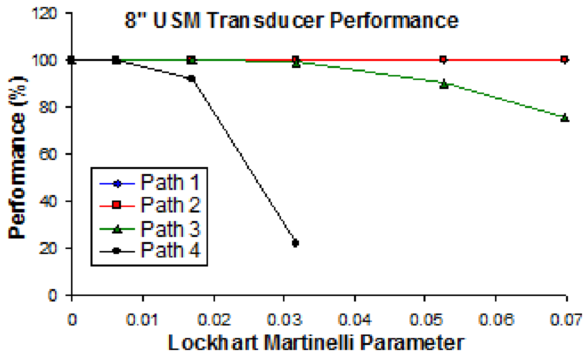

Fig 59. 8”Performance % vs. X_{LM}
Gas / LHC, DR 0.045, Fr_g 2.2.

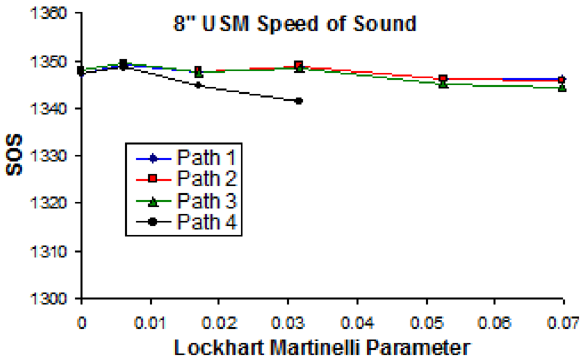

Fig 60. 8” SOS % vs. X_{LM}
Gas / LHC, DR 0.045, Fr_g 2.2.

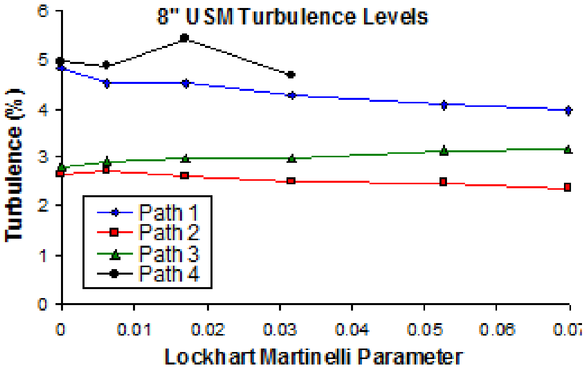

Fig 61. 8”USM Turbulence % vs. X_{LM}
Gas / LHC, DR 0.045, Fr_g 2.2.

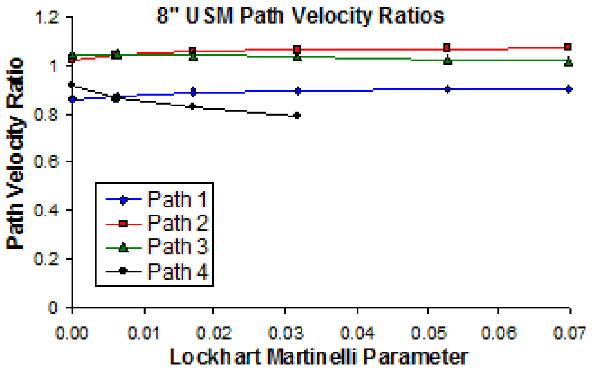

Fig 62. 8” Path Velocity Ratios vs. X_{LM}
Gas / LHC, DR 0.045, Fr_g 2.2.

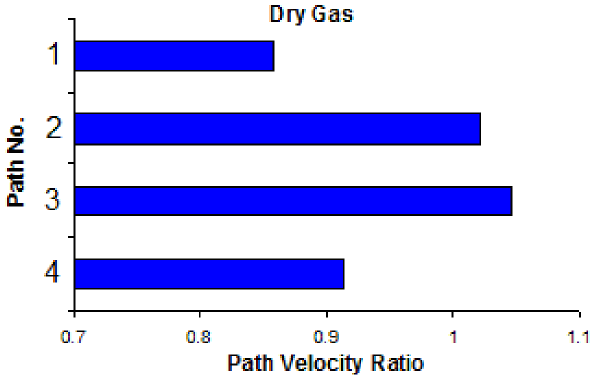

Fig 63. 8”USM Path Velocity Ratio
Gas / LHC, DR 0.045, Fr_g 2.2., Dry Gas

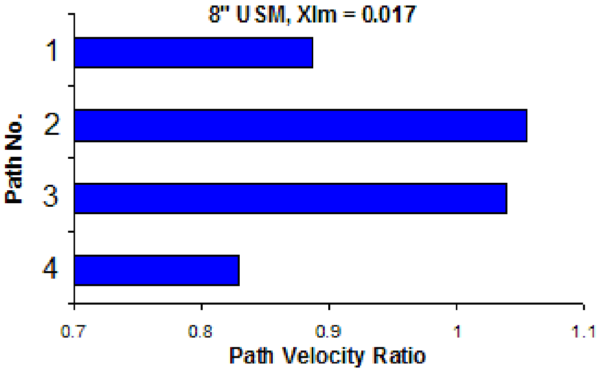

Fig 64. 8” USM Path Velocity Ratio
Gas / LHC, DR 0.045, Fr_g 2.2 X_{LM} 0.017

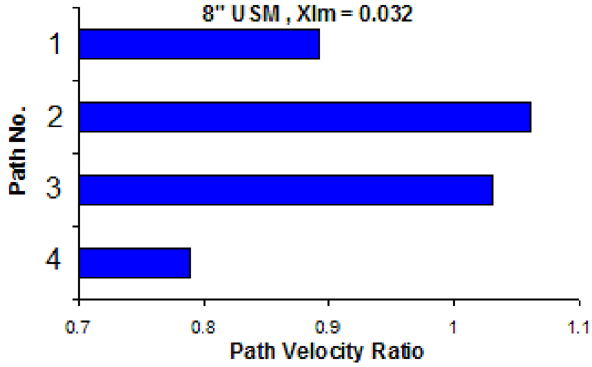

Fig 65. 8”USM Path Velocity Ratio
Gas / LHC, DR 0.045, Fr_g 2.2., X_{LM} 0.032

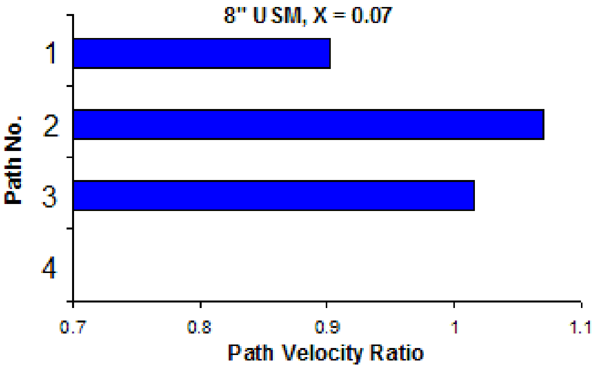

Fig 66. 8” USM Path Velocity Ratio
Gas / LHC, DR 0.045, Fr_g 2.2 X_{LM} 0.07

of about $X_{LM} \geq 0.015$. Path 3 begins to show this abnormality individual Path Velocity Ratio at about $X_{LM} \geq 0.03$. Figure 60 shows the individual path SOS vs. liquid loading. There is no significant SOS warning until Path 4 begins to fail at $X_{LM} > 0.02$. No other path showed any significant SOS problem across the liquid loading range tested. Figure 61 shows the individual path turbulence vs. liquid loading. No clear indication of a problem is evident until Path 4 fails at $X_{LM} > 0.032$. Across the liquid loading range tested no other paths turbulence diagnostic check noticed the presence of wet gas. Figure 62 shows the individual Path Velocity Ratio vs. liquid loading. Again, in this method of presentation it is difficult to see any liquid loading effect. A marginally better way is to look at the individual path velocity ratio plots (see Figures 63 thru 66), but much better still is the PF vs. Symmetry plot (see Figure 67). It can be difficult for an operator to be sure if wet gas flow is the problem when looking at the Path Velocity Ratio plots alone (i.e. Figures 63 thru 66), although the failure of path 4 is a potential wet gas flow indicator. Figure 67 shows a much clearer trend, although it is possible such a result may be caused by other malfunctions causing path 4 to fail. As Path 4 fails at $X_{LM} \geq 0.032$ the PF & Symmetry calculations stop. The lack of data from path 4 at $X_{LM} > 0.032$ indicates failure of the path. A failed path is in itself a diagnostic result. A path fails for a reason, and that reason is obviously causing adverse effects on the metering system. A path 4 failure does not in itself indicate wet gas, but flooding due to the presence of wet gas flow is one possibility for such a failure.

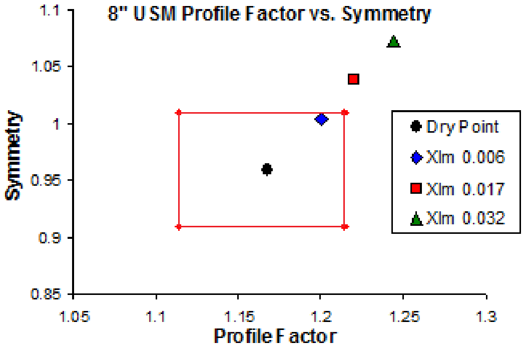

Fig 67. 8” USM PF vs. Symmetry
Gas / LHC, DR 0.045, Fr_g 2.2.

The Venturi meter diagnostic system can show a problem exists and suggests wet gas is the probable cause by a liquid loading of $X_{LM} > 0.002$. The orifice meter diagnostic system can show a problem exists and suggests wet gas is the probable cause by a liquid loading of $X_{LM} > 0.01$. The chordal 4 path ultrasonic meter tested can show an unspecified problem exists by a liquid loading of $X_{LM} > 0.01$. This ultrasonic meter diagnostic system began to show a specific wet gas pattern by $X_{LM} > 0.03$.

7. Conclusions

Wet gas flow is an extremely adverse flow condition that significantly degrades the capabilities of all gas meter technologies. No gas meter can come close to meeting its dry gas performance specifications if more than trace liquid is present. An ISO wet gas meter correlation is not just a useful method of correcting a gas meter’s liquid induced over-reading. For a correlation to be published by ISO there must be a massed data set from multiple meters and test facilities publicly available. This data set has to include data from multiple independent 3rd parties to indicate that the meters wet gas performance is not just repeatable, but reproducible, and therefore predictable. Hence, the existence of an ISO wet gas correlation for any given meter indicates that industry has a comprehensive understanding about that meter technologies wet gas flow performance. This is the case with Venturi and orifice meters. Conversely, the lack of a comprehensive correlation for any given gas meter technology suggests that industry as yet does not fully understand that technologies wet gas flow performance. This is the present state of ultrasonic meter wet gas flow research.

The DP meter has a simple, effective and established liquid loading monitoring system. This DP meter liquid loading monitoring system is well known, extensively tested and developed, described in ISO publications, and has been widely applied for several years. The Venturi meter liquid loading monitoring system is very effective, showing the presence of very small liquid loadings. The orifice meter liquid loading monitoring system is moderately effective, showing the presence of small to moderate liquid loadings. The ultrasonic meter has a single phase diagnostic system that is potentially capable of identifying some unspecified problem exists at low liquid loadings, and identifying wet gas as the likely problem at moderate liquid loadings.

It is not by accident that virtually every wet gas meter on the market (most of which are developed and owned by parent companies that also own DP and ultrasonic single phase gas meter products) use DP meter technology and none utilize ultrasonic meter technology. The ultrasonic meter measures gas flow by multiple discrete velocity measurements across paths. This can be highly effective in single phase metering applications. However, with the highly adverse condition of wet gas flow, the liquid’s presence causes these discrete measurements to fail due to wave scatter, energy absorption, ‘bridging’, path flooding etc. Wet gas causes ultrasonic meters to lose a portion of the signals needed to measure the flow. That is, in an application where more information is beneficial to meter the more complex flow ultrasonic meters tend to produce less information than they can with single phase flow. In contrast, the DP meters interact with and manipulate the wet gas flow, causing the flow pattern to change in a reproducible way through the meter body. This causes the DP signals, still clearly readable, to have a reproducible relationship with the wet gas flow. This is what allows DP meters to have published ISO correlations.

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